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OBSERVATORY. Celestial phenomena have long been observed from buildings or sites specially equipped for the purpose. Notable examples before the early modern period include that at Hamadan (1024), established to remedy tables of planetary positions; at Maragha (1259) in northwest Persia, set up by Genghis Khan's nephew Hulagu, a devotee of astrology, and equipped with renowned astronomers from China to Spain; and at Samarkand (c. 1420), built by Ulugh Beg, grandson of Tamerlane and also a skilled mathematician and astronomer. The main instrument at Samarkand, the largest sextant ever made, consisted of two hinged rods whose free ends roamed over a circular arc 40 meters in radius. Using it, Samarkand's astronomers drew up a catalog of 1,018 stellar positions, the greatest achievement of fifteenth-century observational astronomy. Observatories were yet to be harmonized and integrated into Islamic culture, however. The Istanbul observatory, built in 1577, the year of a famous comet, did not long survive its completion. The faithful suspected that its attempt to pry into the secrets of nature had brought on misfortunes including plague, defeats of Turkish armies, and deaths of important individuals.

The comet of 1577 and an earlier supernova in 1572 undercut Aristotelian astronomical theory in Europe and encouraged the Danish nobleman Tycho Brahe to build an observatory surpassing everything before it. The Danish king, Frederick, offered him the island of Hven. There Tycho built Uraniborg, his manor and observatory, with large instruments for observing stellar and planetary positions, a paper mill and a printing press, and other necessities for self-sufficiency. Its great mural quadrant was a brass quarter-circle arc 2 meters in radius mounted to a wall oriented precisely north-south. Governmental largesse, equivalent to a great many millions in today's dollars, flowed to Tycho during King Frederick's reign and the regency of his son Christian, but shortly after Christian's coronation in 1596 it ceased.

The seventeenth and eighteenth centuries saw the rise of nation-states in Europe and growing sea trade, increasing navigational demands for accurate astronomical data. Charles II of England issued a royal warrant in 1675 appointing John Flamsteed "astronomical observator" at a salary of £100 per year to rectify "the tables of the motions of the heavens, and the places of the fixed stars, so as to find out the so much-desired longitude of places for the perfecting the art of navigation." A second warrant established a small observatory in the royal park at Greenwich. There was no provision for instruments, some of which Flamsteed paid for himself, and which his widow removed from Greenwich.

The Paris Observatory, begun in 1667, though more generously funded by the state, combined the pomp of the French court with poor design. Observing through windows rather than a rotating dome limited observations. The Cassini family ruled the observatory for four generations, until driven out during the French Revolution.

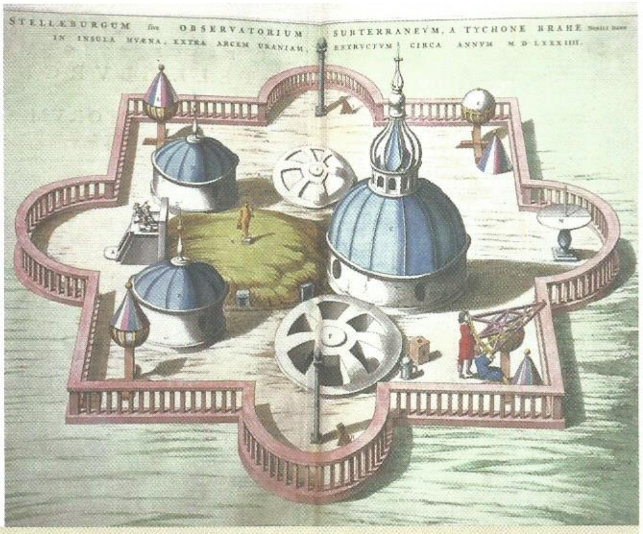
The observatory at St. Petersburg also functioned more for show than science until replaced in 1839 by the Pulkovo Observatory south of the city. Equipped with fine instruments, the new astronomical capital of the world figured as an object of high utility and importance to the scientific honor of Russia. The United States Naval Observatory, devoted, like Pulkovo, to positional astronomy, was completed in 1844, though surreptitiously in the face of congressional disapproval.

President John Quincy Adams in his message to Congress of 1825 had lamented that Europe had 130 "light-houses of the skies" and America none. Soon the United States had observatories too, mostly in colleges. Harvard lured William Cranch Bond away from his private observatory to work for no salary and supply his own instruments. They pointed out windows until interest in the great comet of 1843 led to a public subscription to construct and endow the Harvard College Observatory. The municipal Cincinnati Observatory also was funded by public subscription in 1843. Cincinnati purchased an 11.25-inch refractor from the German firm Merz and Mahler, makers of the Pulkovo 15-inch refractor, then the largest and best telescope in the world. Cincinnati's astronomer spent most of his time displaying the heavens to subscribers. Harvard, too, ordered a telescope from Merz and Mahler, and received a twin to the Pulkovo 15-inch. Trying too hard to justify its purchase, Bond mistakenly reported that he had resolved stars in the Orion nebula.

College and government observatories with precision instruments focused their efforts on positional astronomy. Individuals in small, private observatories were freer to explore new fields. The industrial revolution and British technology facilitated the construction of large metal reflecting telescopes from the 1780s to the 1860s, but steerable mountings and shelter from inclement weather, both important elements of working observatories, lagged in development, leaving the telescopes largely unusable. Application of the new technologies of photography and spectroscopy to astronomy also occurred first in private observatories. In 1854 William Huggins disposed of his silk and linen business and moved to Tulse Hill, a suburb of London, where he set up his own telescopes. By the 1870s, he was identifying elements in the spectra of stars and nebulae and detecting the motion of stars from shifts in their spectral lines.

Huggins's telescopes limited his investigations to bright, relatively near objects. Meanwhile in the United States, men wealthier than the former draper endowed the observatories with more expensive instruments: the Lick Observatory of the University of California with a 36-inch refractor (1887) and the Yerkes Observatory of the University of Chicago with a 40-inch (1897). The Lick, the first of the mountain observatories, demonstrated the value of good astronomical seeing at high altitude.

Growing interest in astrophysics and in distant stars and nebulae encouraged the development of new observatories


STELLÆBURGUM ſive OBSERVATORIUM SUBTERRANEVM, A TYCHONE BRAHE
IN INSULA HVÆNA, EXTRA ARCEM URANIAM, EXTRUCTUM CIRCA ANNUM M D LXXXIIII.

A portion of the observatory built by Tycho Brahe (1546–1601) on the island of Hven in the Danish Sound. From Willem Blaeu, *Atlas* (1665).

with large steerable reflecting telescopes suitable for photography and auxiliary instruments for the analysis of starlight. In 1902, Andrew Carnegie, rich from innovations in the American steel industry, created the Carnegie Institution of Washington to encourage investigation, research, and discovery. George Ellery Hale left the Yerkes Observatory to build, with Carnegie money, the Mount Wilson Observatory on a mountain above Los Angeles. A 60-inch photographic reflecting telescope, completed in 1908, and a 100-inch, completed in 1918, were the largest telescopes in the world and they revolutionized astronomical knowledge. Lights from the expanding city affected astronomical seeing, however, and after World War II an even larger telescope was constructed at Mount Palomar, northeast of San Diego.

The Mount Wilson observatory's relationship with physicists at the nearby California Institute of Technology was also crucial to its dominance of the study of astrophysics during the twentieth century. Many observatory staff at the beginning of the century had acute vision but little scientific education; soon a Ph.D. degree and considerable theoretical understanding were necessary for admittance.

Supposedly only men could withstand the rigors of observing all night in an unheated telescope dome, but the presence of women in observatories kept pace with their progress in university science programs. Women were first employed in an observatory in 1886, at Harvard, for lower wages than men would have received, not to observe but to examine photographs of stellar spectra and catalog the spectral lines.

World War II marked a turning point in the relationship between science and the state. The development of radar, ballistic missiles, and the atomic bomb relied on and demonstrated the power of state-sponsored and directed research and development. Observatories were a major beneficiary of increased government patronage.

Research on radar during World War II had led to the University of Manchester's Jodrell Bank Research Station and its large steerable radio telescope. Government assistance proved insufficient, however, until the observatory was rescued from financial disaster by its ability to track *Sputnik* in 1958. In 1962, British astronomers discovered a radio source that Australian astronomers identified with a faint star; but the honor of measuring the highest redshift observed up to that time and establishing the first known quasar went to the United States, which had the only optical telescope powerful enough to study the object's spectrum. Commonwealth pride was assuaged by the creation of the Anglo-Australian Observatory in New South Wales in 1974.

The Soviet Union's *Sputnik* challenged American aerospace supremacy. The United States responded with a new institution, the National Aeronautics and Space Administration (NASA). Among its accomplishments are automated mini-observatories launched into space, topped off by the two-billion-dollar Hubble Space Telescope. This instrument, operated by the Space Telescope Science Institute, is managed by a university consortium under contract to NASA. Observatory personnel and much of the auxiliary instrumentation are earthbound. In general, NASA adjudicates questions of scientific priority and supplies the money for space observatories; industry helps build them; and universities or consortiums of universities design and operate them, and analyze the resulting observations.

The Kitt Peak National Observatory on a mountain near Tucson supports the largest collection of big telescopes in the northern hemisphere. Seventeen universities have come together in the Association of Universities for Research in Astronomy (AURA) to manage the observatory. After *Sputnik,* the National Science Foundation supplied many millions of dollars for construction of AURA facilities.

Observatories moved from cities to mountain-tops and then into space. They have also moved south, to observe the sky not visible from the Northern Hemisphere. The British Board of Longitude established the Royal Observatory at the Cape of Good Hope in 1820; the Harvard College Observatory had a southern station in Peru at the end of the nineteenth century; and Mount Wilson established a southern station in Las Campanas, Chile, in 1976. Its dark-sky site is better for extragalactic studies than Mount Wilson, which diminished its activity in the 1980s to free up funds for Las Campanas. Chile also boasts AURA's Cerro Tololo Inter-American Observatory and the European Southern Observatory. Astronomers from any institution may apply for observing time, and automation increasingly allows astronomers to control the telescopes from anywhere in the world.

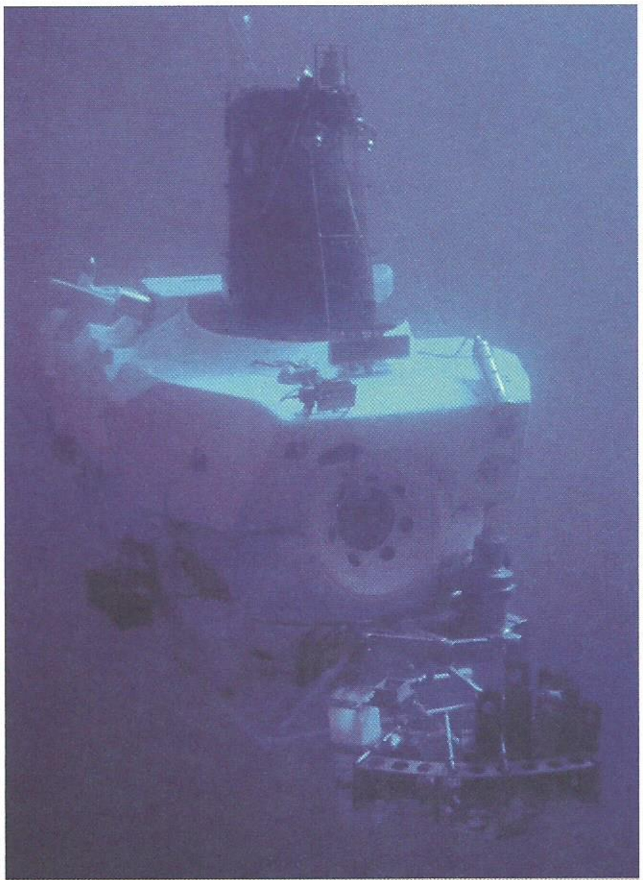
It remains to be seen whether generous governmental patronage for observatories will long outlive the Cold War. Already, though, immense, technologically complex, and expensive observatories on Earth and in space memorialize our civilization as pyramids do ancient Egypt and Mexico, cathedrals the Middle Ages in Europe, and Stonehenge ancient Britain.

NORRISS S. HETHERINGTON

OCEANOGRAPHIC INSTITUTIONS. Most modern oceanographic institutions date from the second half of the twentieth century. During this period, oceanography came from the periphery of earth science to a more central position. Sea-floor studies played a crucial role in establishing current thinking about the dynamics of continents and oceans. Physical oceanographers improved knowledge of the mechanisms governing ocean circulation and the relationship between ocean and atmosphere, with important consequences for understanding climate change. From the 1980s onwards, they joined marine biologists, geologists, and chemists in the study of recently discovered hydrothermal vents and their unique faunas. These developments reflected scientific interests and oceanography's military and other applications in modern industrial society, and took place when funding for large-scale scientific projects became increasingly available. The funding made possible not only new ships and opportunities to explore the oceans on a scale not known before but also a corresponding increase in the number and scale of institutions carrying on marine research.

The first marine laboratories date from the second half of the nineteenth century. By then most nations had organizations such as the United States Coast Survey or the Meteorological Office in Britain, which functioned in the widest sense as oceanographic institutions, and also natural history museums and large aquaria. Zoologists who came to the seaside to be near fresh specimens developed the first dedicated institutions from ad hoc arrangements. A growing awareness of what could be learned about the origins, development, and physiology of living organisms from marine life powered their enthusiasm.

The first permanent institution in Europe was a laboratory dedicated to the study of marine zoology and physiology established by J. J. Coste at Concarneau, France, in 1859. A biological station at Arcachon, maintained by a local scientific society, followed in 1863. By the 1890s, marine stations could be found on the coastlines of Europe from the Black Sea to the Scandinavian Arctic. Of these early foundations the most influential was the Stazione Zoologica established at Naples by the German zoologist Anton Dohrn in 1872. Subsidized by the German government but also supporting itself by renting tables to other scientists and institutions and through the sale of specimens, the Stazione Zoologica provided (and provides) scientists of all nationalities with year-round access to research facilities where studies of the anatomy, physiology and development of marine organisms led to important advances in the life sciences.



The Woods Hole Oceanographic Institution operates the US Navy's Deep Submergence Vehicle *Alvin* to explore hydrothermal vents.

These institutions varied considerably in their origins, modus operandi, and objectives. Félix-Joseph de Lacaze-Duthiers's stations at Roscoff and Banyuls-sur-Mer were linked to his department at the Sorbonne and welcomed visiting workers on the Naples model. Most laboratories opened only seasonally and a few, such as the station founded by the Zoological Society of the Netherlands in 1876 in its early days, occupied prefabricated buildings that could be moved from one location to another. Many of these European institutions received at least part of their funding from the state, some governments (notably the British) being stingier than others. In the United Kingdom, the Marine Biological Association established the Plymouth Laboratory in 1885. Other early British laboratories were connected with university departments (e.g., Gatty/St. Andrews and Port Erin/Liverpool), local societies, and fishery committees. Until well after 1900, British government funding for marine research was largely restricted to fisheries programs and provided at best an insecure lifeline to the independent laboratories.

Meanwhile, in the United States, marine biological laboratories were set up at Woods Hole, at Cold Spring Harbor, and elsewhere. The laboratory at Woods Hole, through its predecessors, the Penikese Laboratory established by Louis Agassiz in 1873 and the Annisquam Sea-side Laboratory of 1880, had its roots in teacher training but would later become a leading center for biological research. On the West coast, the principal centers were linked to universities—the Hopkins Marine Station of Stanford University at Pacific Grove, founded in 1892, the Scripps Institution for Biological Research (University of California), and the University of Washington's Oceanographic Laboratories.

In 1871, the U.S. Commission for Fisheries under Spencer Fullerton Baird selected Woods Hole for biological investigations and built the fisheries laboratory there a few years later. Concern over fisheries drove much organized marine research in the late nineteenth century. Norway channeled its marine research effort into specialist fisheries institutions. Scandinavian scientists soon perceived the need for more broadly based and coordinated studies of fisheries and related problems. Their initiative led to the establishment of the International Council for the Exploration of the Sea in 1900. The ICES inspired the creation of national laboratories and a short-lived (1902–1908) Central Laboratory in Christiania (Oslo) that paid special attention to the development of apparatus.

Until 1900, people considered the study of the oceans a shipboard activity. As the collections gathered in expeditions multiplied, however, land facilities for their study were required. The voyage of HMS *Challenger* (1872–1876) resulted in the creation of the Challenger Office in Edinburgh. It shut down after the completion of its report in 1895. Sir John Murray continued its work independently at the Villa Medusa until his death in 1914 but in 1884 he had established a laboratory that he hoped would be more permanent, the Scottish Marine Station for Scientific Research near Granton—the world's first truly oceanographic institution. In spite of Murray's efforts to conform to the prevailing utilitarian ethos by linking the station to long-running research by the Scottish Meteorological Society on the effects of weather on fisheries, the government refused to support it. The Marine Biological Station at Millport, established by the West of Scotland Marine Biological Association in 1897, regarded itself as Murray's successor and its work on productivity in the 1920s and 1930s followed his interdisciplinary vision.

The first permanent oceanographic institutions date from the turn of the twentieth century. The geographer Ferdinand von Richthofen established the Institut für Meereskunde in Berlin in 1900 to cover all aspects of oceanography. It sponsored the influential *Meteor* expedition in the 1920s, which resulted in the first detailed survey of the deep Atlantic circulation. After World War II the Berlin institute's work was transferred to a like-named, preexisting institution attached to the University of Kiel. Kiel was already distinguished in ocean research through the work of Otto Krümmel, whose *Handbuch der Ozeanographie* served as a standard text, and of Victor Hensen and other members of the Kiel school of plankton studies.

One of the foremost leaders of ocean research of the early twentieth century was Prince Albert I of Monaco, an enthusiast for science, education, and international cooperation. His wealth enabled him to mount numerous scientific voyages in Atlantic, Mediterranean, and Arctic waters from the 1880s till 1914. He set up his twin foundations, the Institut Océanographique in Paris and the Musée Océanographique at Monaco, both still in existence, to house his collections and promote the science of the sea through research and teaching.

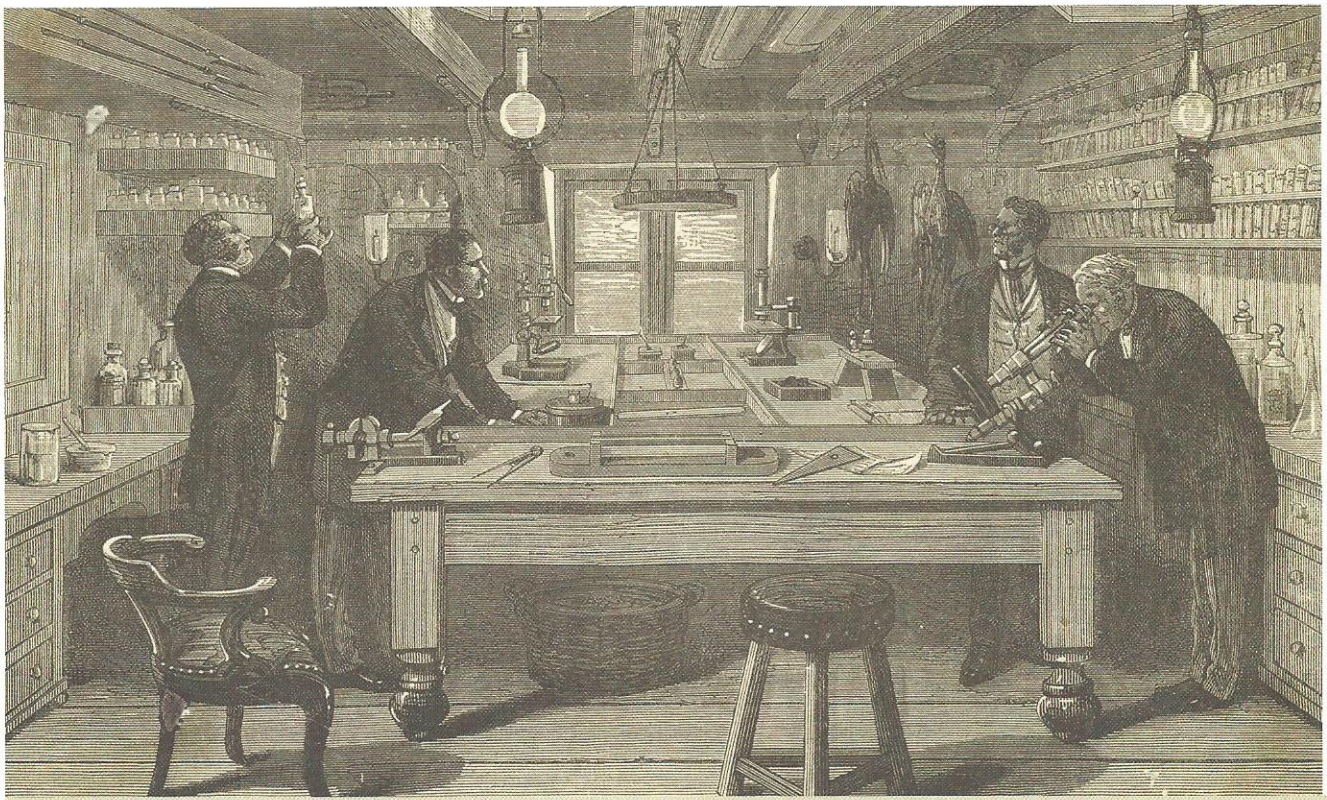
After World War II, Admiralty pressure led to the establishment of a (British) National Institute of Oceanography (1949), now incorporated in the large-scale Southampton Oceanography Centre, established in 1995.

In the United States, concern about the state of marine science prompted several initiatives in the interwar period. In 1923, William E. Ritter secured the appointment of Thomas Wayland Vaughan as his successor as director of the renamed Scripps Institution of Oceanography (SIO) of the University of California. However, only after the appointment of the Norwegian physicist Harald Ulrik Sverdrup as Vaughan's successor in 1936 did work expand offshore into the Pacific Ocean. The outbreak of war postponed major development until the 1950s. Since that time SIO has been the premier U.S. West-coast oceanographic institution. On the eastern seaboard, this position is held by the Woods Hole Oceanographic Institution, founded in 1930 when a committee of the National Academy of Sciences enlisted the support of the Rockefeller Foundation for physical oceanography. A key role has also been played by the Lamont-Doherty Geological Observatory of Columbia University, founded by Maurice Ewing in 1948 as a center for seafloor studies.

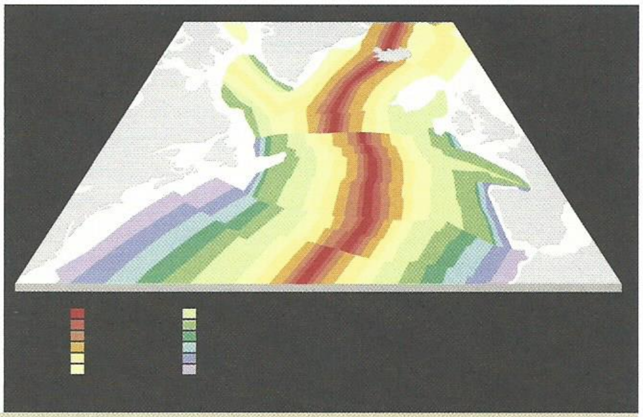
The diversification of ocean science during recent decades, ranging from the deep-sea research to increasingly comprehensive observations of the oceans from space, has brought many sorts of institutions, including commercial enterprises, into oceanographic work. National and international academic cooperation now maximizes efficiency in what is still an expensive and challenging field of scientific investigation. However, large institutions continue to play an important role as centers of excellence, both in generating and supporting new research projects.

MARGARET B. DEACON

OCEANOGRAPHY, as a distinct scientific discipline, and "oceanography," as the standard term for the study of all of the marine sciences, both date from the late nineteenth century, when the first major expeditions were undertaken specifically to explore the physics, chemistry, biology, and geology of the world's oceans. But the prehistory of oceanography begins centuries earlier. Natural philosophers had given attention separately to most of the branches that now constitute oceanography—Aristotle's investigations of



The zoological laboratory on board the British research ship *Challenger* in 1874



Computer graphic indicating the changes in magnetism in sea floor volcanic rocks as Earth's magnetic field changes over time. The red strip represents the mid-Atlantic ridge (rocks 0-0.2 million years old), the purple strips the continental margins (rocks up to 200 million years old).

marine invertebrates; Robert Boyle's analysis of the temperature, salinity, and movement of sea-water; and Isaac Newton's explanation of the forces that cause the tides being among the most famous.

The first text devoted exclusively to marine science was the *Histoire physique de la mer* (1725) of Count Luigi Ferdinando Marsigli, a military man and founder of the Istituto di Bologna. From studies of the Gulf of Lyons, Marsigli assembled information about water temperature, salinity, specific gravity, tides, waves, currents, depth contours, and marine plants and animals. The diligence required in these efforts convinced Marsigli of the limitations of individual research in marine science; larger scale results required teams of investigators and government support—the hallmarks of oceanography since the nineteenth century.

The second half of the eighteenth century witnessed an acceleration of marine research. Enthusiasm for, and advances in, chemistry underpinned the chemical analysis of sea water by leading chemists, including Antoine-Laurent Lavoisier and Torbern Bergman. Salinity was also studied during voyages of exploration, such as the Danish expedition to Arabia Felix, and, especially, James Cook's expeditions in the Pacific. Meanwhile, ocean currents and circulation patterns engaged the curiosity not just of sailors but of scientists such as Benjamin Franklin, chronicler of the Gulf Stream, and Benjamin Thompson, Count Rumford, whose heat experiments led him to attribute ocean circulation to differences in water density, a theory finally accepted after a long delay.

Studies of currents and tides intensified in the early nineteenth century, exemplified by British naval surveyor James Rennell's *An Investigation of the Currents of the Atlantic Ocean* (1832). Also in the 1830s, John Lubbock and William Whewell, Lubbock's mentor at Trinity College, Cambridge, reduced tidal phenomena to mathematical analysis. And the British Admiralty helped to install tidal gauges around the southern coast of England. The limitations of the data for establishing general tidal patterns, and for drawing what Whewell dubbed "cotidal lines," led him to develop an international scheme for the collection of information about tides. The nascent British Association for the Advancement of Science soon took over the program. At the U.S. Naval Observatory, Matthew Fontaine Maury assembled data on winds, currents, and other oceanographic phenomena from ships' captains, and published the results in his textbook, *The Physical Geography of the Sea and Its Meteorology* (8 editions, 1855–1861).

The British Association also played a key role in marine biological enterprises during the middle decades of the nineteenth century. The chief investigator was Edward Forbes, a marine naturalist and paleontologist for the Geological Survey, and a native of the Isle of Man. Excursions of small boats to ascertain the depth and distribution of bottom-dwelling species led to summer-long cruises in British waters, continued aboard Admiralty ships in the late 1860s by naturalists Charles Wyville Thomson and William B. Carpenter. The success of these efforts, and the increasing curiosity about life and conditions in the deep oceans, gave rise to the most ambitious oceanographic endeavor of the era, the expedition of HMS *Challenger* (1872–1876). Wyville Thomson headed a team of five scientists and an artist during this three-and-a-half-year circumnavigation of the globe. They oversaw dredging and trawling at more than 360 stations. International authorities in the various subspecialties analyzed the data and the specimens collected. The resulting *Challenger Reports* (1885–1895), published in fifty volumes, remain the founding benchmark of oceanographic science.

Although the supremacy of its navy allowed England to take a leading role initially, other nations used the precedent to launch important oceanographic enterprises during the late nineteenth and early twentieth centuries. Germany focused initially on the North Sea, but its S. S. *Gazelle* also operated in the Atlantic at the same time as the *Challenger,* and its S. S. *National* (1889) carried out a global Plankton Expedition. Alexander Agassiz headed American cruises in the Atlantic aboard the *Blake,* and in the Pacific aboard the *Albatross.* France, Denmark, Italy, and Russia had also launched projects by the turn of the twentieth century. This period saw the creation of the first marine biological laboratories, the prototype being the Stazione Zoologica created at Naples in 1873 by Anton Dohrn.

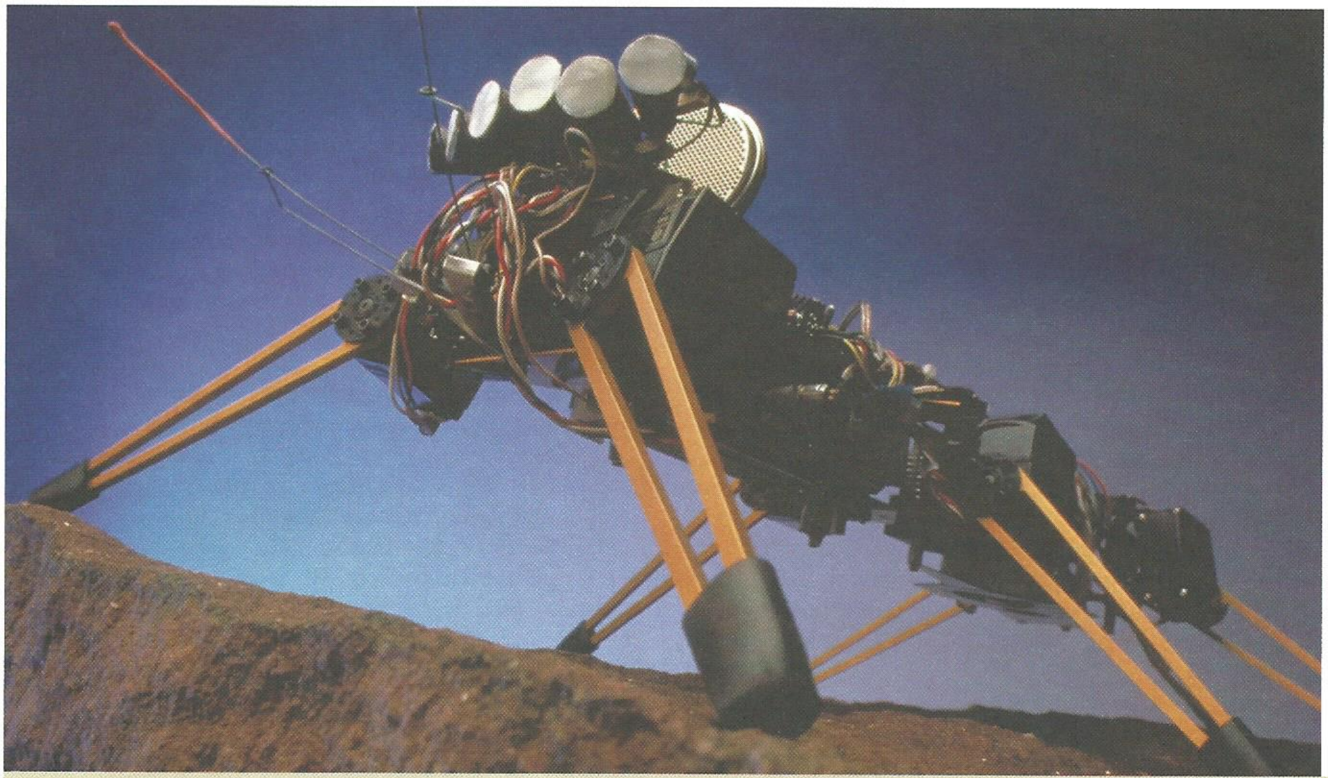
The two world wars provided an unprecedented stimulus to physical oceanography at the expense of marine biology. The deployment of submarines and their detection by sonar brought new urgency to studies of bathymetry and the relation of temperature, salinity, and bottom sediments to acoustic transmission. And an intimate knowledge of waves, currents, and surf conditions would become crucial later on to the success of amphibious landings. By World War II, a productive, if sometimes stormy, collaboration had emerged between civilian oceanographers and naval officers. In the United States, the principal centers of this collaboration were the Woods Hole Oceanographic Institution in Massachusetts, headed by Columbus O'Donnell Iselin, and the Scripps Oceanographic Institution in California, under the direction of Harald U. Sverdrup. In the midst of the war, Sverdrup, with co-authors Martin W. Johnson and Richard H. Fleming, published the first modern textbook of oceanography, *The Oceans: Their Physics, Chemistry, and General Biology* (1942).

After 1945, the Cold War relentlessly drove the growth of oceanography. As early as 1950, the U.S. Navy defined Soviet submarines patterned after advanced German designs seized at the war's end as the greatest maritime threat to the security of the United States. Understanding the ocean environment became critical to antisubmarine warfare. The Office of Naval Research and the Bureau of Ships quickly and regularly made resources available to address the threat, funding work by hundreds of scientists and institutions around the country. The results quickly outstripped administrative efforts to bring disciplinary coherence and recognition to oceanography, slowing the creation of degree programs and formal technical education at major universities. However, this massive investment made at a dizzying pace resulted in amazingly comprehensive ocean surveys, the understanding and exploitation of the deep sound channel, fundamental advances in sonar, the very rapid development of ocean acoustics as a field of study, the creation of the Navy's ocean surveillance system (SOSUS), the quieting of nuclear and conventional submarines, and the possibility of submerged missile launching. In addition, these circumstances effectively launched the careers of Roger Revelle, Walter Munk, J. Lamar Worzel, Dale Leipper, Waldo Lyon, Henry Stommel, Alan Robinson, and many others. The new sophistication of oceanography made it possible for American nuclear attack submarines to detect and shadow their Soviet missile-carrying counterparts. The deep ocean quickly became the front line in the Cold War.

The Russians followed suit, responding to American determination for the same reasons. While definitely competitive in terms of theoretical understanding and scientific capability, the material resources of the former Soviet Union did not permit it to keep pace. However, its scientists made very significant contributions to understanding antisubmarine acoustics, the study of the Arctic region, ocean surveying, and the construction of advanced oceanographic vessels.

Twentieth-century oceanography achieved a new, mathematically rigorous understanding of the coupling of atmospheric and oceanic phenomena, and of the climatic implications of oceanographic events such as El Niño. But after World War II, the discipline turned increasingly toward questions of marine geology and geophysics. The leading catalyst here was the continental-drift hypothesis proposed by Alfred Wegener in his book *The Origin of Continents and Oceans* (1915, first English translation 1924). Rejecting notions of continental stability and isostasy, Wegener proposed that the present configuration of the continents, and other phenomena from stratigraphy, paleontology, and biogeography, could be accounted for by assuming the gradual movement of the continents horizontally over the face of the globe. The theory gained few adherents until the 1960s, by which time new lines of evidence helped bring about the plate-tectonics revolution. Evidence came from studies of paleomagnetism and polar wandering carried out by P. M. S. Blackett, S. Keith Runcorn, and their colleagues in Britain; heat flow from mid-ocean ridges by British geophysicist Edward Bullard; seismological activity along mid-ocean ridges by Americans Maurice Ewing and Bruce Heezen; and gravity anomalies, pioneered by the Dutch geophysicist Felix Andries Vening-Meinesz and the American Harry H. Hess. In 1960, Hess proposed the hypothesis, subsequently known as sea-floor spreading, that would explain all of these phenomena. In the mid-1960s, the British geophysicists Frederick Vine and Drummond Matthews confirmed the hypothesis by analyzing patterns of magnetic anomalies around mid-ocean ridges, and the *Glomar Challenger* drilled directly into the Mid-Atlantic Ridge. J. Tuzo Wilson's 1965 concept that the earth's surface consists of several rigid but mobile plates put the finishing touch on the plate tectonics revolution.

OPERATIONS RESEARCH. One of the progenitors of Operations Research (OR), the physicist P. M. S. Blackett, defined it as "social science done in collaboration with and on behalf of executives," but this was both too modest and too limited a definition. Originally forged as a species of interdisciplinary scientific research in the fires of World War II, OR proved to be a major innovation in the management of science and in the application of natural-science models to social phenomena during the postwar period.



Autonomous microrover Genghis from MIT's Artificial Intelligence Laboratory. The overall length of this apparent monster is one foot.

OR began as an Anglo-American response to the vast expansion of the funding and organization of science by the military from 1940 onward. Mixed disciplinary units dominated by physicists rationalized the deployment of novel weapons systems such as radar and mechanized air warfare, and parlayed their scientific expertise into advice for developing a new science of war. OR arose in an Anglo-American context of science organization; the German war effort produced no equivalent, perhaps because German scientists were already well integrated into state bureaucracies. The forerunner of OR, "operational analysis," came into existence in Britain with the Tizard Committee on air defense in 1935; by 1942, several OR groups had become established in military structures in the United States. What in Britain had been a method to optimize the sinking of submarines by altering the color of the attacking airplane, the depth of the torpedo, the angle of attack, and other variables grew in America to encompass the modeling of the targeting of ICBMs as a two-player game with various technological options solved with a Monte Carlo simulation.

Having spread throughout the military in the immediate postwar period, OR subsequently entered business schools as part of the toolkit of academic training for corporate middle management. In 1952, the Operations Research Society of America was formed, providing the professional identity for a haphazard collection of trained natural scientists and mathematicians. Although OR maintained its connections to physics and other natural sciences, recruitment in the second half of the century tended to come increasingly from its own professional base. Thus it became possible to regard OR in the late twentieth century as a social science with an unusually specialized clientele.

OR cannot be reduced to a few discrete doctrines, since its methods tended to diverge between the British and American professions after World War II. Whereas British OR generally maintained its original character as a hands-on project of pragmatic modeling based on thermodynamic metaphors and statistical expertise, American OR, inspired by the contributions of John von Neumann in the areas of game theory and computers, grew into a mathematically abstract and theoretical discipline including "systems analysis" and "decision theory" at the RAND Corporation and Bell Laboratories. Some of the most illustrious scientists of the postwar period spent portions of their careers as operations researchers, including P. M. S. Blackett, J. D. Bernal, Conrad Waddington, Philip Morse, George Gamow, William Shockley, John Bardeen, Kenneth Arrow, and Ivan Getting.

The standard curriculum for an operations researcher toward the end of the twentieth century included linear programming, network models, game theory, inventory models, queuing theory, information theory, econometrics, and simulation techniques. OR progressively became allied with "behavioral science," artificial intelligence, cognitive psychology, organization theory, and neoclassical economics. It became the exemplar of the "cyborg sciences" primarily because of its heavy reliance on the computer as a source of legitimation and metaphoric inspiration, as well as its penchant for blurring the conceptual boundaries between men and machines.

Although OR and systems analysis have succeeded as intrinsically interdisciplinary professions, their practitioners experience recurrent bouts of self-doubt about the true or fundamental core competencies of the profession. Initially, the operations researcher regarded himself as a technocratic consultant who reconciled planning with market allocation or military command hierarchy. As planning ambitions receded, the role of the mathematical consultant moved to the fore. Hence, OR has never achieved an altogether stable academic identity, tending to become lodged in schools of management or public policy, but sometimes in departments of mathematics, natural science, or engineering. OR has been predominantly client-driven rather than content-based throughout its half-century of existence; nonetheless, it has played an indispensable role in forging a rapprochement between academic science and the state.

Philip Mirowski

OPTICS AND VISION. During the early seventeenth century, Johannes Kepler, echoing the earlier views of Leonardo da Vinci, likened the eye to a camera obscura, a black box containing a pinhole opening through which an image of external objects is projected on the back wall. Kepler worried that the analogy implied that the eye must invert the images it observes, but his work on light, optics, and the camera obscura forced him to accept the inference. He concluded that light forms images on the back wall of the eye, now called the retina, and not on the crystalline humor, now called the lens, as most scholars of the period thought.

Kepler argued that light as a passive entity followed the laws of geometry. His *Astronomiae pars optica* (1604) and *Dioptrice* (1611) dealt with the refraction of light, whose "law"—a relation between the angle of incidence i and the angle of refraction r—was given in 1621 by Willebrord Snel, professor of mathematics at the University of Leyden, who busied himself with astronomical and triangulation studies. Snel did not print his result; René Descartes, who may have seen it in manuscript, published it in 1637 as $\sin r = (\sin i)/n$, where n, the index of refraction, is a constant. Christiaan Huygens elaborated upon the law of refraction in his *Traité de la lumière* of 1690 by assuming that light was undulatory, rather than corpuscular, in nature. Like Kepler, Huygens believed that refraction arises because light moves more slowly in a denser than in a rarer medium.

Descartes had accounted for vision by analogy. According to him, the colors we perceive, like the impulses transmitted by a blind man's stick, result from pressure. He took color to be a secondary quality, not a property of external objects but the mind's interpretation of the pressure registered on the optic nerve. Nicolas Malebranche deepened Descartes's theory of vision in his *De la recherche de la verité* (1688). Sight cannot ascertain the truth of things in themselves; its purpose is to facilitate our navigation through the world. Further to the impugning of vision, George Berkeley (*Essay towards a New Theory of Vision*, 1709) undermined the idea that the concepts the mind creates by working on sense impressions reliably indicate the nature of things.

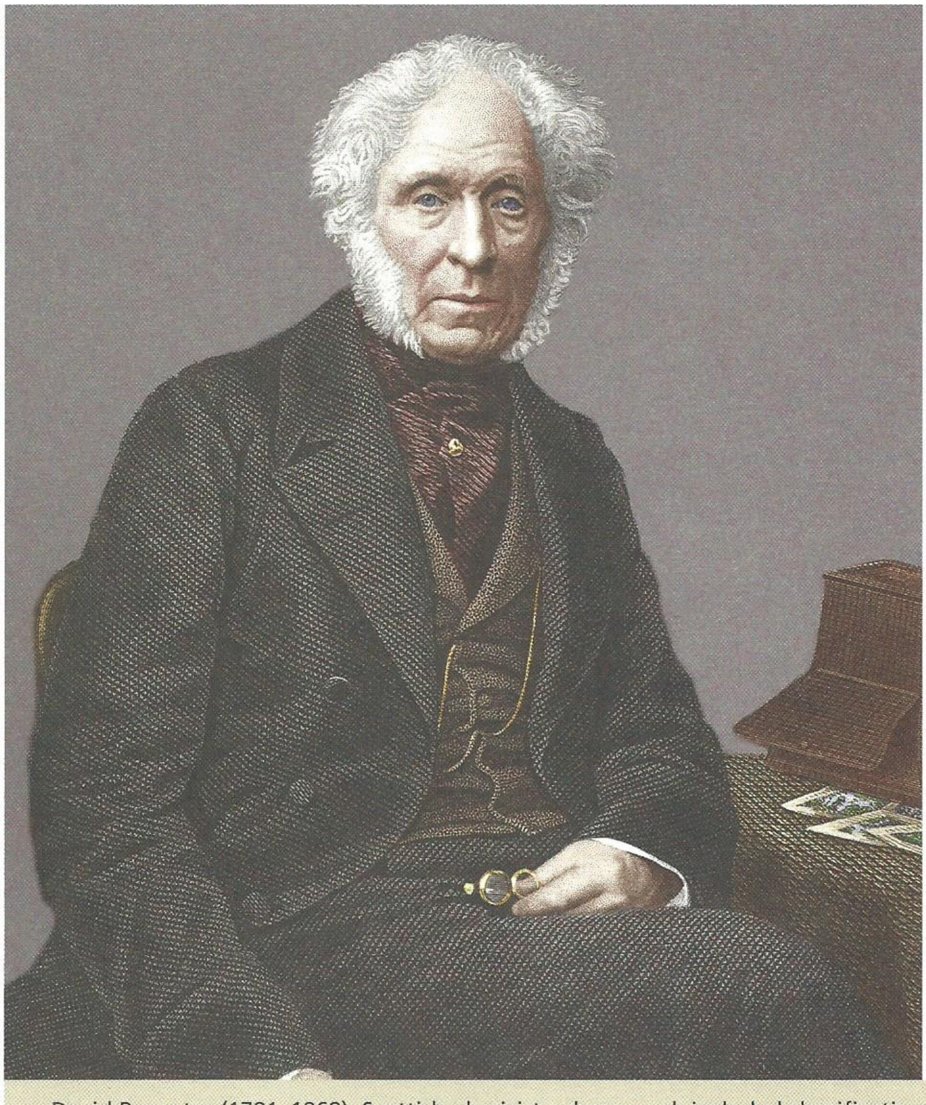
Isaac Newton's grand discovery, that sunlight is made up of rays of different refrangibilities, transformed the study of light and vision. Newton showed in 1672 and at length in his *Opticks* of 1704 that sunlight passed through a glass prism yielded a spectrum of rays of different colors refracted at characteristic angles; that the rays of a given color all had the same refrangibility (and so could not be further divided by a prism); and that the differently colored rays, if reunited by a second prism, again produced white light (the so-called experimentum crucis). Newton supposed that the different rays were made up of particles; but to explain why some rays striking glass are refracted and others reflected, as well as to model interference phenomena like the colors of the plates and "Newton's rings," he also supposed that the particles interacted with a pervasive subtle matter or ether. The emission and motion of the particles set the ether in vibration, and the particles penetrated or rebounded from a surface in accordance with the phase or "fit" of vibration of the ether there.

The different refrangibilities of rays of different colors make single lenses cast colored images. Newton thought, mistakenly, that this evil could not be cured, and he turned his attention to the construction of reflecting telescopes. In the 1750s, the instrument-maker John Dollond proved Newton wrong by manufacturing achromatic doublets made of crown and flint glass, which compensated one another's dispersion. Drawing upon Dollond's idea of an achromatic doublet, Joseph Fraunhofer, a Bavarian skilled artisan and optician working in the secularized Benedictine monastery of Benediktbeuern, improved upon a complex glass-stirring technique first developed by Pierre Louis Guinand, a Swiss bell pourer. With this method, Fraunhofer was able to manufacture flint glass of unprecedented homogeneity in the 1810s and 1820s. In addition to this crucial technological development, Fraunhofer reckoned that he could use the dark lines of the solar spectrum (later called the Fraunhofer lines), which his superior glass prisms produced, to demarcate precise portions of the spectrum. By altering the ingredients of his glass samples, he adjusted the refractive and dispersive properties in order to produce a second lens that would correct for the chromatic aberration produced by the first. After Fraunhofer's death in 1826, the British firm Chance Brothers of Birmingham and the French company Feil of Paris usurped the world's optical glass market from Bavaria. But during the 1880s, the physicist Ernst Abbe and chemist and glassmaker Otto Friedrich Schott manufactured apochromatic lenses for the Carl Zeiss Company in Jena, Germany, which would monopolize optical glass and equipment production until World War II.

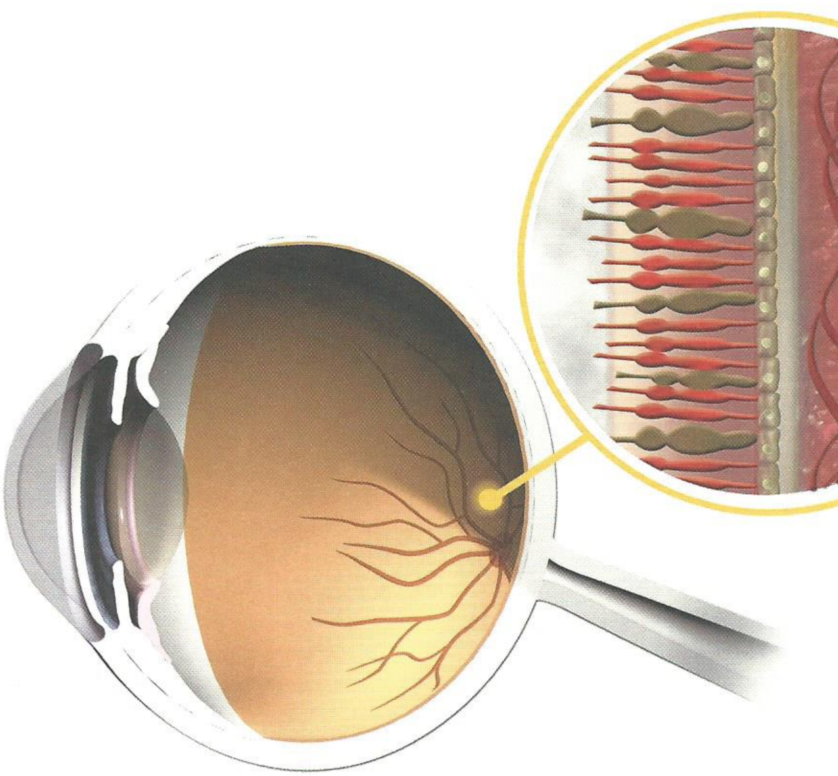
During the eighteenth century, prominent natural philosophers like Leonhard Euler and Benjamin Franklin challenged Newton's particulate model of light, but their opposition, based on qualitative considerations such as the improbable loss of matter from the sun that the model implied, did not make an effective alternative. The corpuscular theory reached its pinnacle after 1800 in the school of Pierre-Simon de Laplace, which developed a quantitative theory of optical phenomena based on distance forces between light particles and the particles of ponderable matter. They managed to incorporate the polarization of light, which Huygens had known in the case of birefringent crystals and Étienne Louis Malus had discovered in 1810 in light reflected from glass, into their scheme by supposing that light particles had different properties on different "sides."

The remarkable success and high patronage of the corpuscular theory did not preserve it from an attack launched around 1800 by the English physician Thomas Young, who drew upon an analogy between sound, which was understood to be a wave motion in air, and light. Young perceived a further, and more useful, analogy between diffraction patterns and the interference of water waves. In 1807, he presented the persuasive demonstration (now famous as the Young double-slit experiment) in which light from a common source passes through two parallel narrow slits in an opaque screen. The superposition of the two transmitted beams on a surface beyond and parallel to the screen produces dark and light stripes rather than clear images of the slits.

Young's initiative was continued by a better mathematician than he, Augustin Fresnel, whose memoirs, composed between 1815 and 1827, challenged his compatriots who championed the corpuscular theory. One of Fresnel's techniques was to treat each point of the wave front as a source of secondary waves, a technique introduced by Huygens. By adding the contributions of those secondary waves in accordance with Young's principle of interference, Fresnel could determine the intensity of light in a diffraction pattern. The Laplacian Simeon-Denis Poisson deduced from Fresnel's



David Brewster (1781–1868), Scottish physicist, whose work included classification of the optical properties of crystals and minerals, the invention of the kaleidoscope, and the discovery of Brewster's law governing the polarization of light by reflection



Light enters the eye through the cornea (colored grey), passes the lens (brown and pink) partly covered by the iris (blue), and lands on the retina (orange). There light receptors (red and brown) transform the stimulus into impulses fed by the optic nerve (grey) to the brain.

equations the paradoxical result that a bright spot should appear at the center of the geometrical shadow of a disk illuminated by a beam of light. The experiment decided in favor of Fresnel.

Around 1862, James Clerk Maxwell calculated that the speed of propagation of an electromagnetic field is approximately that of the speed of light. He concluded that light must consist of transverse waves of the same medium, which, according to the ideas of Michael Faraday, gives rise to electric and magnetic phenomena. British physicists attempted to ascertain the physical properties of this ubiquitous and omnicompetent ether. To incorporate polarization into the theory, both Young and Fresnel independently suggested that the vibrations constituting light are perpendicular to the direction of travel, not, as in the model proposed by Huygens and, originally, Young, in the direction of travel, as is the case of sound in air. With this addition, the wave theory bettered the corpuscular theory at its strongest point. All efforts to find a mechanical model for the ether failed, and the assumption that one might exist came into increasing conflict with electromagnetic theory. The nature of light and the fate of its medium were resolved—for the twentieth century at least—by the theory of relativity and quantum physics.

Young contributed to the study of vision as well as the theory of light by criticizing the custom of separating consideration of the physical and mental states involved in the perception of color. He argued that the eye, being far less complex than the mind, simplifies the information provided by a particular scene and channels it to the brain, which in turn paints the scene. He demonstrated that the most sensitive points of the retina, which are connected directly to the brain, can detect only the three primary colors—blue, red, and yellow. The optic nerve is composed of filaments, portions of which correspond to a primary color. The brain mixes the sensations to create all the possible colors. Young's theory was ignored until Maxwell and Hermann von Helmholtz elaborated upon his work in the mid-nineteenth century. Individuals suffering from color blindness (a disorder first recognized during Young's lifetime) have an abnormally low number of retinal cones, which detect color.

With the help of the opthalmoscope he invented in 1851, Helmholtz demonstrated that the optic nerve itself is insensitive to light. Sensory nerves apparently merely transmitted stimuli between the end organs and the sensorium. Between 1852 and 1855, Helmholtz studied color mixing and vision. He based his further work on Young's theory of three distinct modes of sensation of the retina, which he had previously rejected. He adopted the interpretation in Maxwell's paper, "Experiments on Colour, as Perceived by the Eye" (1855), which stated as Young's theory the proposition that, although monochromatic light stimulates all three modes of sensation, only one or two color responses will prevail in the resulting mixed color. This reading made one of the foundations for Helmholtz's *Handbuch der Physiologischen Optik* of 1860. In this classic work, Helmholtz developed Young's notion of three distinct sets of nerve fibers, although he observed that three distinct and independent processes might take place in each retinal fiber.

Binocular vision presented another set of physical-psychological problems. Charles Wheatstone's stereoscope, invented in 1838, played a critical role in the debate over how perception transforms two flat, monocular fields into a single, binocular field illustrating objects in relief. One group, led by David Brewster, argued for a theory of projection according to which the mind imagines lines starting at two stimulated points on the retinas and projecting outward to their point of intersection at the observed object. Another theory, proffered by the German physiologist Johannes Peter Müller, argued that retinas possess pairs of corresponding or identical points, each pair providing only one point in the unified field of vision. Wheatstone's stereoscope seemed to disprove Müller's views.

Physiologist Ewald Hering challenged Helmholtz's work on vision, declaring that four primary colors—red, blue, green, and yellow—formed the psychological basis for all color sensation. Hues arrange themselves in opposing pairs: red/green and blue/yellow. Helmholtz characterized the controversy as a clash between opposing epistemologies, nativism (Hering's position) and empiricism (his own view). At a deeper level, Hering opposed reckoning the processes of perception in analogy to functions of the human mind. He viewed vision as immediate impressions on the eyes and so rejected theories of projection in favor of a theory of identity similar to Müller's. Against Wheatstone and Brewster, Hering demanded that corresponding pairs of retinal points determine visual directions and depth perception. Helmholtz argued that the processes governing our spatial perception are psychological in nature and thus conditioned by learning and experience.

The controversy lasted well into the 1920s. Modern research affirms both the Young-Helmholtz three-color theory and Hering's four-color theory. The two theories complement one another. While the trichromatic approach explains how the eye detects and perceives color, Hering's explains how color information is encoded and sent to the brain via the nerve pathways. Research during the 1960s and 1970s confirmed that the eye contains three types of color sensors, the photoreceptors, composed of red, green, and blue cones, so-called because of their absorption of light at those wavelengths.

Myles Jackson

OZONE HOLE, a colloquial term for the dramatic seasonal thinning of middle atmospheric ozone (O_3, an allotrope of oxygen) over Antarctica. The controversy over the causes of this phenomenon is a defining episode in the history and politics of anthropogenic global climate change.

In the mid-1920s, the English meteorologist Gordon Dobson made observations of atmospheric ozone employing a global network of spectrophotometers of his own design. The total amount of atmospheric ozone is today expressed in Dobson Units, where 1 DU equals 0.01 mm. If all the ozone in the atmosphere were compressed into a single layer, that layer would be about 300 DU (3 mm) thick.

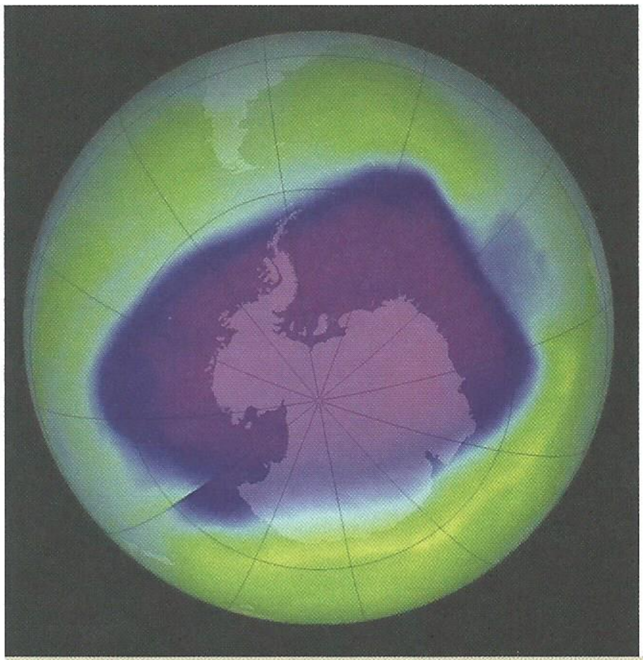
Between 1929 and 1931, the British geophysicist Sydney Chapman hypothesized that ozone arises by the action of ultraviolet light on molecular oxygen (O_2) in what is sometimes called the Chapman layer at about 45 km, a figure now lowered to a variable altitude between 15 and 30 km. Chapman's ideas about atmospheric ozone dominated the scene until 1964.

By 1970, it was clear that the chemistry of stratospheric ozone involved hydrogen, nitrogen (predicted by the Dutch meteorologist Paul Crutzen), and chlorine. In 1974, the Mexican chemist Mario Molina and the American chemist Sherwood Rowland argued that CFCs (chlorofluorocarbons), inert chemicals widely used for sixty years as aerosol propellants and refrigerants, were finding their way into the stratosphere, where they dissociated under intense ultraviolet radiation and produced chlorine species that combined with photolytically dissociated oxygen, thus preventing the formation of ozone; they predicted a long-term decline in the earth's protective ozone shield. It also appeared that aircraft and spacecraft exhausts (the SST and the Space Shuttle) would therefore also deplete atmospheric ozone.

Although these discoveries led to some regulatory efforts in the 1970s to reduce CFCs, especially in the form of aerosol propellants, economic and political interests, as well as legitimate scientific disagreement about the causes of ozone depletion, stymied attempts to control ozone-depleting chemicals. Debate intensified when the British Antarctic Survey reported in 1984 that Antarctic ozone levels had plummeted by a third since 1977 (to less than 200 DU). Americans initially doubted these results, since the TOMS (Total Ozone Mapping Spectrometer) on the *Nimbus-7* satellite had not detected sharply lower levels of ozone. Later analysis of the satellite's programming showed that it had been ordered to disregard such low values as outside the "reasonable range," though they had been regularly observed since 1978.

Regulatory efforts to cut CFCs and other depleting chemicals resumed in the 1980s, including the signing of the Montreal Protocol (1987). Nonetheless, the Antarctic ozone hole has continued to grow. In 1998, it covered 27 million km^2, and in 1999, total atmospheric ozone in October fell below 88 DU. The magnitudes of these changes were not predicted in 1985 by any model of stratospheric composition, even looking fifty and a hundred years ahead. Susan Solomon, the scientist who in 1987 proposed that the ozone hole was a direct consequence of the activation of anthropogenic chlorine on stratospheric ice clouds (later experimentally confirmed many times over), has said that the period of our complacency concerning this ozone hole, and our doubts as to its cause, are over.

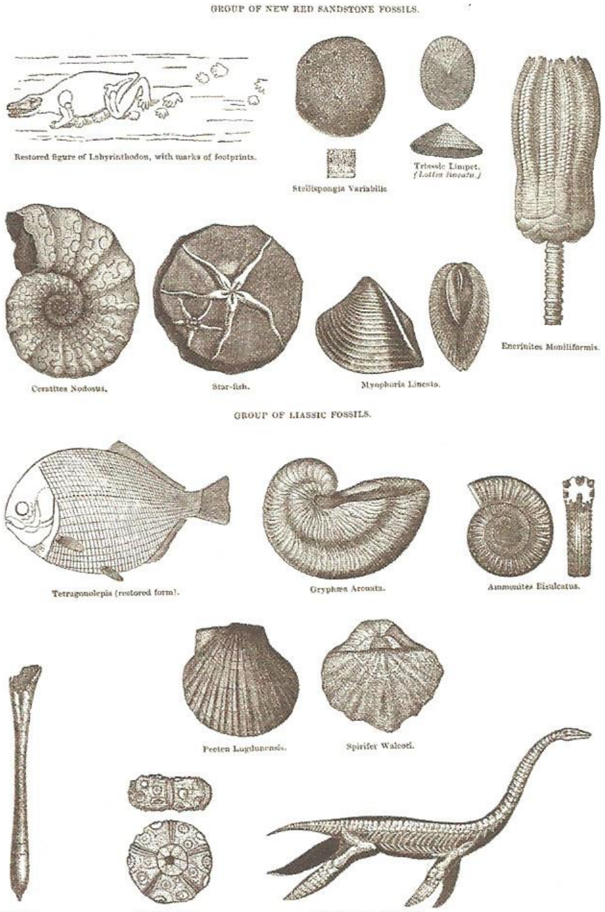
Mott T. Greene



Colored satellite image of low-atmosphere ozone levels over Antarctica on September 25, 2006. The lowest level is indicated by purple, the highest by yellow; the hole pictured covers 29.5 million square kilometers, a record.

P

PALEONTOLOGY. Paleontology, the study of the remains of living beings and their traces in the rocks, emerged as a distinct area of investigation in the late eighteenth and early nineteenth centuries. By then, most mineralogists and naturalists concurred that fossils were the remains of living beings. The German naturalist Johann Friedrich Blumenbach went further, and argued that in the past many animals and plants had become extinct while new and different ones had been created in their place. Two of his followers, Ernst von Schlotheim and Georges Cuvier, realized this meant that extinct species and genera could be used to identify and correlate stratified rocks. In an important study of the geology of the region around Paris published in 1812, Cuvier, used fossil quadrupeds for the purpose. Schlotheim embarked on the massive task of classifying the less glamorous but much more widely distributed invertebrate fossils, as a preliminary to using them in stratigraphy. Not long after, in 1816, the English surveyor William Smith published his *Strata Identified by Organized Fossils.* By the 1830s, British geologists, ignoring the Continental tradition, claimed that Smith should be credited with the discovery that fossils could be used to identify strata.


GROUP OF NEW RED SANDSTONE FOSSILS.
Restored figure of Labyrinthodon, with marks of footprints.
Steilispongia Variabilis
Triassic Limpet. (Lottia lineata.)
Encrinites Moniliformis.
Ceratites Nodosus,
Star-fish.
Myophoria Lineata.
GROUP OF LIASSIC FOSSILS.
Tetragonolepis (restored form).
Gryphæa Arcuata.
Ammonites Bisulcatus.
Pecten Lugdunensis.
Spirifer Walcoti.
Belemnites.
Cidaris Coronata.
Plesiosaurus Dolichodeirus.

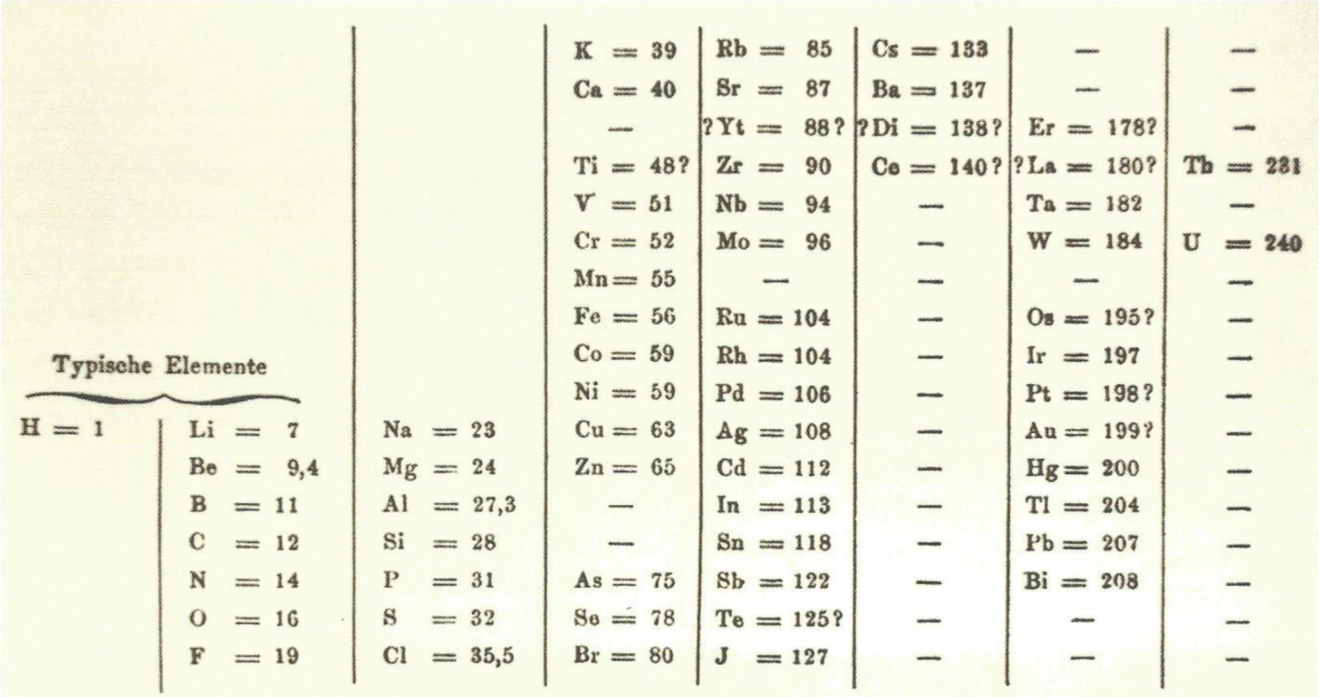
Historical artwork of various invertebrate and vertebrate fossils, taken from *The Circle of the Sciences*, published in 1862–7

Whatever the merits of this dispute, geologists agreed that fossils offered the best way to determine when a stratum was formed and to correlate strata over large distances. They busied themselves collecting, identifying, cataloguing, and producing monographs on the fossils most useful in stratigraphy. Overwhelmingly these were marine invertebrate fossils, usually shells of one kind or another, but also corals, trilobites, ammonites, belemnites, and so on. Geologists also studied fossil plants, especially abundant in the economically important coal-bearing formations. With the possible exception of fishes, vertebrate fossils were too rarely preserved to be of use.

In the 1870s, paleontology matured as a scientific discipline with its own specialist journals, meetings, and societies. Although university departments employed paleontologists, the new specialty derived the bulk of its institutional support by being an ancillary to stratigraphy, which was of great economic importance first in the mining industry and later in the petroleum industry as well. Jobs were offered in national geological surveys and later in laboratories run by oil companies. Because of the small diameters of the rock cores brought up in drilling for oil, paleontologists turned in earnest to the study of fossils visible only under the microscope, such as ostracods, foraminifera, and pollen grains. In 1917, the American Association of Petroleum Geologists was formed. By the end of the century, it would be the largest geological society in the world.

For stratigraphic and economic purposes, questions about the meaning of fossils—how life had been created and evolved, how dinosaurs had lived, how man had evolved—were irrelevant. Chemists, biologists, enthusiastic amateurs, and anthropologists were as likely to pursue these questions as paleontologists. Most important debates within professional paleontology dealt with matters that bore directly on stratigraphy. Was a single fossil species or genera adequate to identify a formation, or did the paleontologist have to take whole assemblages of fossils into account? Did whole fossil faunas and floras change abruptly and simultaneously, as Cuvier claimed? Or did they change slowly and gradually, as Charles Lyell contested? Were fossils reliable as indicators of the relative age of rocks? From the early nineteenth century on, geologists had recognized that different extinct species, just like different living species, lived in different environments. If so, was it possible that fossils varied with the environment in which they had been deposited, and not with time? By the late nineteenth century, geologists used the concept of facies to describe these environments, and began to factor environmental factors into their stratigraphic investigations.

In two areas, paleontologists concerned themselves with issues outside stratigraphy. One was paleo-ecology. In the late nineteenth century, German and Russian scientists



Typische Elemente

			K = 39	Rb = 85	Cs = 133	—	—
			Ca = 40	Sr = 87	Ba = 137	—	—
			—	?Yt = 88?	?Di = 138?	Er = 178?	—
			Ti = 48?	Zr = 90	Ce = 140?	?La = 180?	Th = 231
			V = 51	Nb = 94	—	Ta = 182	—
			Cr = 52	Mo = 96	—	W = 184	U = 240
			Mn = 55	—	—	—	—
			Fe = 56	Ru = 104	—	Os = 195?	—
			Co = 59	Rh = 104	—	Ir = 197	—
			Ni = 59	Pd = 106	—	Pt = 198?	—
H = 1	Li = 7	Na = 23	Cu = 63	Ag = 108	—	Au = 199?	—
	Be = 9,4	Mg = 24	Zn = 65	Cd = 112	—	Hg = 200	—
	B = 11	Al = 27,3	—	In = 113	—	Tl = 204	—
	C = 12	Si = 28	—	Sn = 118	—	Pb = 207	—
	N = 14	P = 31	As = 75	Sb = 122	—	Bi = 208	—
	O = 16	S = 32	Se = 78	Te = 125?	—	—	—
	F = 19	Cl = 35,5	Br = 80	J = 127	—	—	—

The periodic table of the elements in the form first given it by Dmitri Ivanovich Mendeleyev (1834–1907) in 1869

began using fossils to reconstruct past climates, past environments, and past shorelines. They studied the environments of living marine invertebrates, for example, to shed light on the environment in which trilobites might have lived. They used the distribution of fossil coral reefs to infer what earlier climates were like.

The other area was the Cambrian boundary, below which paleontologists had failed to find any traces of life. Above it, fossils appeared abruptly as rather specialized invertebrate animals. In the mid-twentieth century, paleontologists detected microscopic unicellular animals and sedimentary structures built up of colonies of algae and bacteria (called stromatolites). The reason for the puzzlingly abrupt change, they concluded, was that until the beginning of the Cambrian, almost all life on earth consisted of simple unicellular bacteria, algae, and protozoans.

Following World War II, as funding within universities and new and powerful instruments became more readily available, paleontologists began asking a wider range of questions. Paleoecologists used the ratios of stable isotopes of oxygen in fossils to trace temperature fluctuations in past oceans. Other paleontologists used the trace amounts of nucleic compounds preserved in fossils to shed light on evolutionary affinities and relationships. More traditional paleontology used the scanning electron microscope to subdivide strata from the Mesozoic to the present in quite remarkable detail.

RACHEL LAUDAN

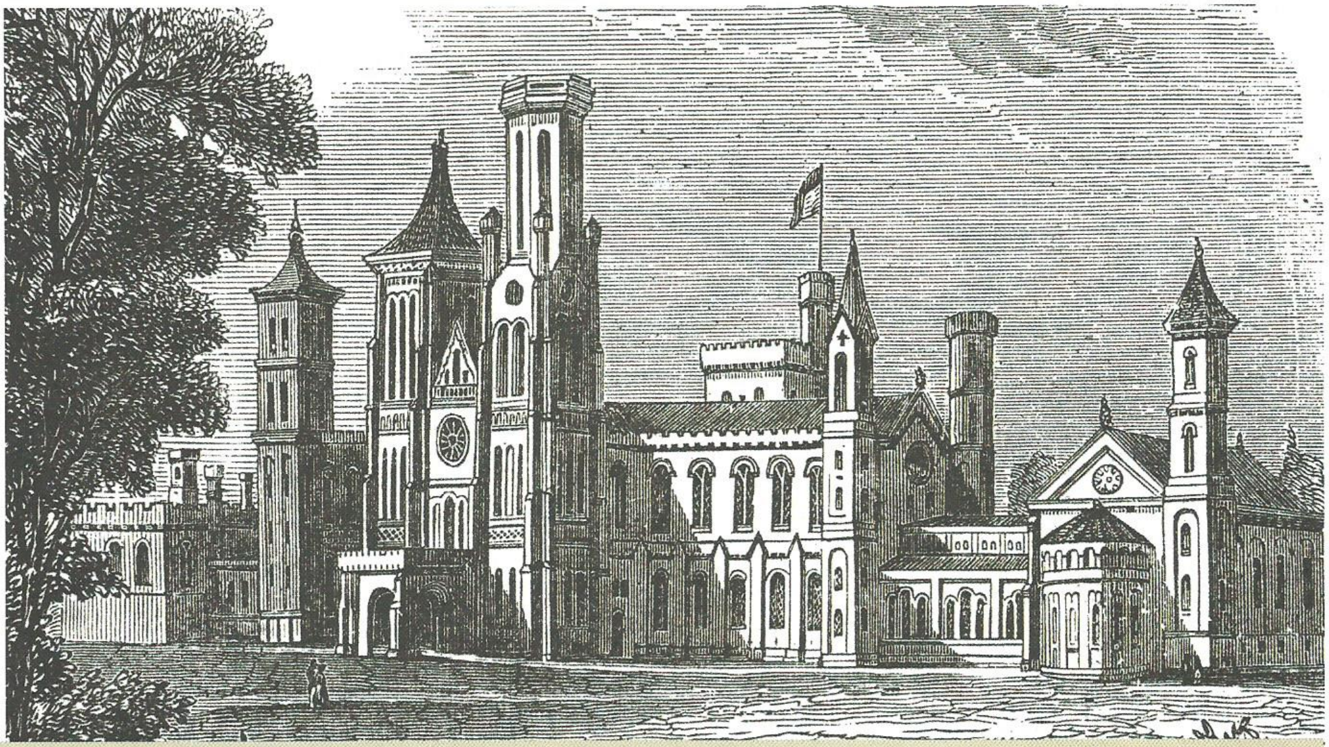
PERIODIC TABLE. Chemists of the early nineteenth century had to rely on indirect methods, analogies, and simplifying assumptions to determine the relative atomic weights of elements, and thus did not reach a consensus on them. Gradually, however, methods improved, and at the international Karlsruhe Congress of 1860 Stanislao Cannizzaro advocated what is, in essence, the system still in use today.

Even before agreement on a single set of atomic weights, several theorists noticed that chemical and physical properties reappeared in a regular, periodic fashion in the various elements. Among these predecessors of the periodic law were Johann Wolfgang Döbereiner, John Newlands, William Odling, and Jean-Baptiste-André Dumas. Many others proposed partial periodic classifications of the elements.

Dmitrii Mendeleev reaped the success of these endeavors. (The German chemist Lothar Meyer pursued a closely parallel path independently, and published his similar contribution shortly after Mendeleev's.) Mendeleev arranged the elements horizontally according to increasing atomic weight, and started a new row below the first whenever similar properties in the elements reappeared. The resulting semirectangular table of atomic weights showed many intriguing regularities. The horizontal rows ("periods" or "series") and the vertical columns ("groups" or "families") revealed a "periodic law." For example, Mendeleev's arrangement placed the alkali metals (sodium, potassium, and the then recently discovered rubidium and cesium) in a single vertical group with a marked family resemblance. The set of next-heavier elements to each of these alkali metals formed a second family group, the alkaline earth metals (magnesium, calcium, strontium, and barium).

This example understates the magnitude of the problems Mendeleev faced, for the elements simply failed to order themselves neatly. (Sometimes the greatest genius requires *ignoring* a certain number of anomalies, while discerning the larger pattern hidden within the data.) Lithium, for instance, fell into the alkali metal group by weight order, but it seemed to have more family resemblance to magnesium than to sodium, the element directly below it in the table. By the same token, beryllium seemed to resemble aluminum more than its putative family member below, magnesium. In certain other cases two adjacent elements seemed to come in a different order by weight from that dictated by the family groupings. For the first anomaly, Mendeleev provided an extenuating rationale; for the second, he did not hesitate to violate the weight order and reverse the two elements in the chart, hence preserving the periodicity of properties.

Despite the problems, Mendeleev had sufficient confidence in the periodic system he published in 1869 to hazard predic-



The Smithsonian Institution in Washington, D.C., in the 19th century

tions based on it. Leaving vacant places in his chart in certain critical instances, he predicted the properties of undiscovered elements. For example, he left a space between calcium and titanium, and two between zinc and arsenic. Here Mendeleev used a strategy that converted yet another anomaly—holes in his periodic table—into potentially powerful evidence for the validity of his discovery. But of course there he risked the danger that his system would fail the test of prediction.

The first of Mendeleev's predicted new elements, discovered by Paul Lecoq de Boisbaudran in 1875, was named "gallium" in honor of France. Gallium's atomic weight of about 70 came close to Mendeleev's prediction of 68, its density of 5.9 grams per cubic centimeter virtually coincided with the prediction, its valence and oxide pattern were as expected, and a long list of observed chemical properties also matched what Mendeleev had forecast. Four years later scandium filled another space, and in another seven years, germanium. Three times Mendeleev had triumphed, not only with the fact of the discoveries, but with the details of physical and especially chemical properties as well.

These confirmed predictions caught the attention of the scientific world. For the first few years after Mendeleev announced his periodic system, it received almost no notice in journals and textbooks, and much less agreement as to its utility. After the discovery of gallium, however, textbook accounts of the periodic law began to appear, and in the 1880s discussions of periodicity of the elements became a common, though not invariable, feature of chemistry textbooks.

Further developments provided both challenges to, and support for, Mendeleev's system. Chemists and then physicists confirmed the weight inversions that Mendeleev had insisted upon to preserve periodicity. A dozen or more chemically similar "rare earth elements" discovered in the last quarter of the nineteenth century presented a more worrisome problem in that they did not fit into any periodic system. Eventually chemists grouped them together in an aperiodic category as "lanthanides." In the 1890s, William Ramsay and Lord Rayleigh discovered the inert gases argon, helium, neon, krypton, and xenon. They fit perfectly by weight before the alkalis, and soon after the turn of the century chemists decided to create an extra group for them at one end or the other of the periodic chart.

The development of atomic physics in the early twentieth century provided an independent method for assigning positions for elements in the periodic table: the measurement of their "atomic numbers." At the same time the study of radioactivity revealed a number of apparently elementary bodies that did not fit into the table; the solution was to enlarge the concept of element. A group analogous to the lanthanides, the actinides, has been added to accommodate transuranic elements.

A. J. Rocke

PHILANTHROPY. Rooted in the moral imperative of disinterested aid of others, philanthropy has been associated with the support of worthy causes at least since the rise of market capitalism. In the modern era, philanthropy increasingly has been directed at institutions and individuals for the increase of knowledge, distinguishing it in some degree from charity (amelioration of human misery) and patronage (support of talented individuals or groups). Substantial philanthropic support has long been a distinctive feature of modern Western science.

Many examples from the history of early modern science illustrate the point. A Medici prince supported the Accademia del Cimento in Florence (1657–1667); seventeenth-century predecessors of the Académie Royale des Sciences in France depended on patrons; and King Frederick II of Denmark financed Tycho Brahe's installation at Uraniborg. In the eighteenth century, Joseph Priestley had support from the Earl of Shelburne, Jean André Deluc from the queen of England, and many small continental academies from local magnates.

The growing institutionalization of science in the early nineteenth century is reflected in the philanthropy of Benjamin Thompson, Count Rumford, who created a research prize, helped found the Royal Institution of Great Britain, and left an endowment for a scientific chair at Harvard University. The philanthropic creation of prizes and premiums established a valuable, if post facto, source of financing. Privately endowed university chairs in the sciences helped to give science a permanent role in higher education.

Perhaps the most dramatic instance of philanthropy in science in the nineteenth century was the Englishman James Smithson's bequest of 1826 to found in the city of Washington an institution devoted to the increase and diffusion of knowledge. Finally organized in 1846, the Smithsonian Institution quickly though briefly became the most significant center of scientific research and publication in the United States. American financiers and industrialists soon began to endow chairs and to create science schools (at Harvard and Yale, for example) and entire universities (Chicago, Clark, Johns Hopkins, Stanford). James Lick, a California entrepreneur, greatly enlarged the scale of philanthropy for science by donating $700,000 to build the world's largest telescope, the 36-inch Lick refractor, which began operation in 1888.

The cumulative effect of small donations could also be substantial. Ormsby Mitchell raised funds for a telescope and observatory in Cincinnati in 1842–1843 by asking local residents for money. A public subscription to publish Louis Agassiz's natural history researches in 1855 was the first nationwide appeal in support of science in the United States; Agassiz personally raised half a million dollars from many sources for his museum at Harvard in the 1850s and 1860s. In 1885, the Pasteur Institute in Paris was founded on broad support from French citizens. Still, in most cases substantial wealth provided the infrastructure for science: Boston's monied class built Harvard's first scientific building, Boylston Hall (1858), and the executor of the Hull fortune funded the biological laboratory at the University of Chicago (1897).

Buildings, university chairs, and astronomical instruments were traditional expressions of philanthropy usually intended to memorialize the donors. Identifying worthy research and researchers required more of the giver as science developed theories and vocabularies beyond the understanding of most educated persons. To pursue leading-edge science demanded tapping various sources for support; Albert A. Michelson and Edward Morley received a grant from the National Academy of Sciences's Bache Fund for their light-wave studies in the 1880s, but their equipment came from local manufacturers who provided it free or below cost. Some philanthropists understood the need: in the 1890s Catherine Wolfe Bruce gave a cumulative $175,000 to researchers around the country to purchase astronomical research instruments, and the Naples Zoological Station in Italy received funds from Alexander H. Davis, a New York businessman, particularly to provide facilities for American researchers.

Although the organized philanthropy of large foundations became the dominant means of nongovernment support of science early in the twentieth century, private philanthropy remained important. In the United States, the Cold Spring Harbor Laboratory was established in 1923 on the basis of private gifts, as was the Institute for Advanced Study (founded 1930), a haven for exiled European scientists. In Europe the Kaiser-Wilhelm-Gesellschaft was created in 1911 with the support of many German bankers and industrialists; the Weizmann Institute of Science in Israel began with gifts that created the Sieff Research Institute in 1934; the Huancayo Laboratory of the Institute of Andean Biology in Peru was built with private funds in 1940; industrialist J. R. D. Tata endowed the Tata Institute of Fundamental Research at Mumbai in India in 1945. Typically, personal philanthropy created new scientific institutions or supported existing institutions, rather than the scientists themselves, and was increasingly shaped by both organized solicitation and tax laws.

The largest private benefactions set up medical foundations, for example, the Wellcome Trust (1936) and the Howard Hughes Medical Institute (1953). Other philanthropy focused on agricultural development, disease, environmental issues, or population control, often directing their programs toward the developing world. As the twenty-first century dawned, Johns Hopkins University received a gift of one hundred million dollars for research on malaria, a scourge of tropical Africa and south Asia.

Philanthropy on a scale that can influence science has derived largely from wealth accumulated in market-capitalist environments. While it has accounted for only a small proportion of science funding and has been limited in the developing world and virtually absent from nations with socialist systems, philanthropy has dramatically affected the conduct of science in many fields and institutions.

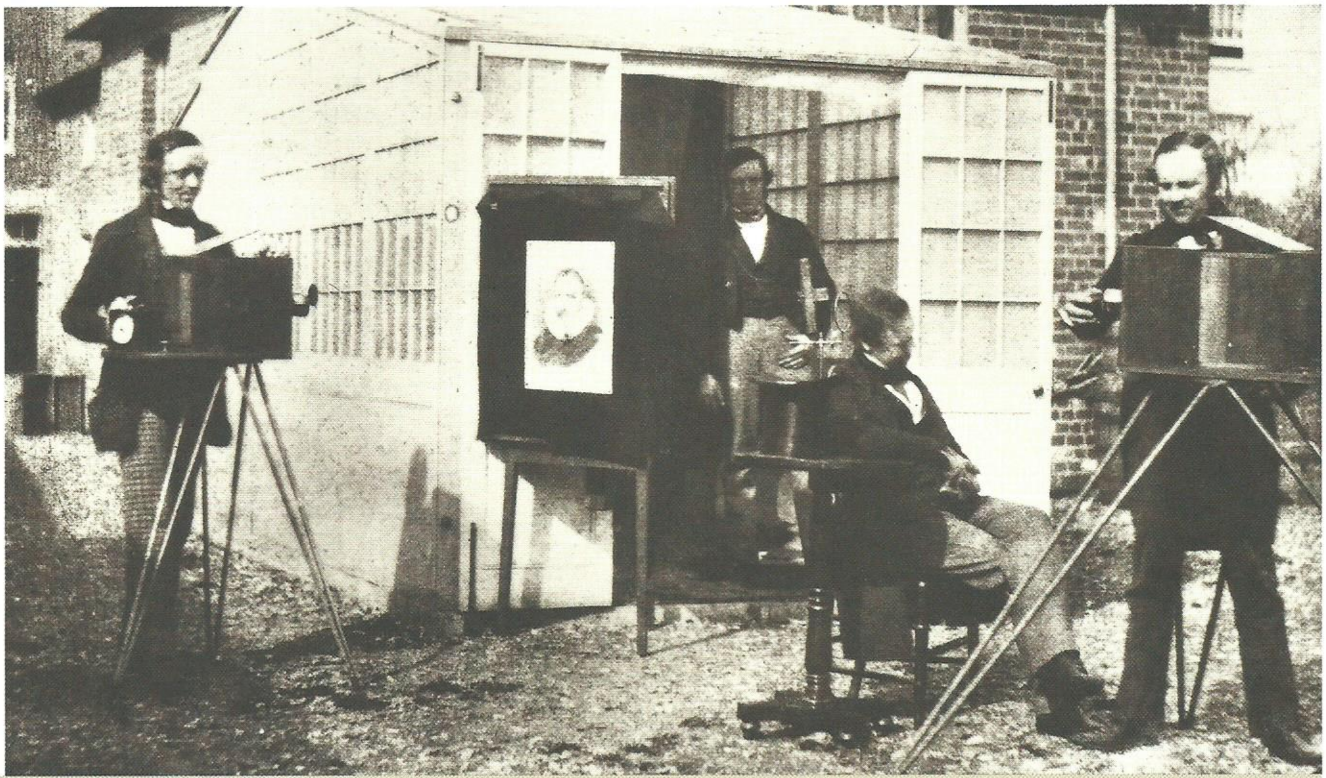
DARWIN H. STAPLETON

PHOTOGRAPHY. The technical history of photography comprises three parallel developments: camera negatives, monochrome positive prints, and recording color. The practice of photography was empirically led throughout its first hundred years, frequently outstripping the ability of contemporary science to explain the various phenomena.

Since the late Renaissance, it had been known that sunlight darkens salts of silver. In 1725, Johann Heinrich Schulze used sunlit stencils to cast images on suspensions of silver salts. Carl Scheele showed in 1777 that the violet rays of the prismatic spectrum were most effective in decomposing silver chloride, the dark product being finely divided silver. During the 1790s, Thomas Wedgwood sun-printed "profiles" of objects onto paper and leather moistened with silver nitrate, but could not prevent their obliteration by daylight. Images in the *camera obscura* were too faint to make any impression, but Wedgwood successfully obtained "copies" of specimens projected by the solar microscope.

The earliest extant camera photograph was not produced in silver, but by *heliography,* a copying process invented by Joseph Nicéphore Niépce in the 1820s. The process places a thin coating of bitumen on a pewter plate, selectively hardens it by sunlight, then dissolves it by oil of lavender to bring out the image. In 1827, Niépce captured the first photograph—now in the Gernsheim Collection of the University of Texas—by a heliographic camera exposure estimated to have taken several days. Heliography was better suited to providing etching-resists for photomechanical printing plates. Attention returned to silver; in 1837, Louis Jacques Mandé Daguerre discovered, fortuitously, that mercury vapor could develop camera images on iodized surfaces of silver-plated copper, the chemical prerequisite, iodine, having been discovered by Bernard Courtois in 1811. The *daguerreotype* process, first publicized in 1839, enjoyed widespread commercial success until photography on paper and glass replaced it in the mid-1850s.

Meanwhile, William Henry Fox Talbot had independently devised *photogenic drawing paper* by 1835. He had noted that the light-sensitivity of silver chloride, precipi-



A Talbotype photography taken in 1845 shows the printing establishment set up by William Henry Fox Talbot (1800–1877) in Reading, England.

tated within the paper's fibers, diminished with excess salt, and had thereby discovered the first method for fixing silver images. Talbot's earliest camera negative (1835) is in the National Museum of Photography, Film and Television in Bradford, England. On hearing in 1839 of Talbot's innovation, Sir John Herschel, who originated the terms "photography," "the negative," and "the positive," demonstrated that unchanged silver chloride in a photograph dissolved in a solution of hyposulfite of soda (sodium thiosulfate). Herschel's "hypo-fixing" superseded Talbot's salt-fixing, and remains in use today. In 1839, Talbot also noted the greater sensitivity of silver bromide—now the chief constituent of all modern photographic materials—made possible by Antoine Jerome Balard's isolation of bromine in 1826.

In 1840, Talbot made his third, crucial discovery: that an invisibly weak dormant picture in silver iodide could be brought out by gallic acid, effectively increasing the speed of his camera photography a hundredfold—from hours to minutes. He named this process *calotype,* and patented it in 1841. Although science could not account for these phenomena of latency and development, Talbot had set photography on the path of continuous refinement for the next 150 years. A quest was mounted for shorter camera exposures and higher resolution. The opacity and texture of paper were avoided by suspending the silver halide in organic binders, making "emulsions" (an inaccurate term, but universally employed): hens' egg-white (Claude Félix Abel Niépce de Saint-Victor, 1847), collodion (Frederick Scott Archer, 1851), and finally gelatin (Richard Leach Maddox, 1871). Emulsions were coated on transparent supports ranging from glass plates (Niépce de Saint-Victor, 1847) and waxed paper (Gustave Le Gray, 1851) to the flexible, but dangerously flammable early plastic, celluloid (cellulose nitrate), which permitted the design of roll-film cameras, introduced by George Eastman in 1888. Modern safety films employ polymer bases of cellulose triacetate (1923) or polyethylene terephthalate (1955). Parallel improvements were made in the optical design of camera lenses, notably achromats (Charles and Vincent Chevalier, 1828), large aperture lenses (Josef Petzval, 1841), rapid rectilinear lenses (J. H. Dallmeyer and H. A. Steinheil, 1866), and Zeiss anastigmats (Paul Rudolph and Ernst Abbe, 1890).

Pure silver halides respond only to blue light and the ultraviolet, whose discovery by Johann Wilhelm Ritter in 1801 represents the first contribution of photography to science. To render tonally balanced negatives, emulsions must react to the entire visible spectrum. Sensitizing with dyes, introduced in 1873 by Hermann Wilhelm Vogel, extended the response to green (orthochromatic plates, 1884), and then red wavelengths (panchromatic plates, 1904), reaching the near-infrared by the 1930s. Sensitometry, the photometric study of emulsion response, was originated by Ferdinand Hurter and Vero Charles Driffield in 1890, accompanied by extensive chemical exploration for better developers, such as hydroquinone (William de Wiveleslie Abney, 1880).

The emulsion binder in universal use by 1900, animal gelatin, displayed great variability in speed. In 1926, Samuel Edward Sheppard detected the cause: traces of sulfur-containing substances, arising from the animals' diet, could sensitize silver halides. Modern emulsion technology now uses pure gelatin, with controlled addition of sulfur and gold compounds as sensitizers. Understanding the latent image became possible with the foundation of solid-state physics and chemistry during the 1920s, especially Yakov Ilyich Frenkel's theory of ionic conductivity and A. H. Wilson's electronic band theory. In 1938, Sir Nevill Francis Mott and R. W. Gurney put forward a mechanism for the formation of the latent image that has found wide acceptance. Because of the granular structure of the developed image, photographic speed is linked inversely to resolution. This tradeoff was improved in the 1980s by controlled growth of silver halide crystals with a tabular habit, increasing their surface-to-volume ratio. The speed of modern negative emulsions is approaching the theoretical limit.

As Talbot realized in 1835, printing positives is an essential procedure to rectify the reversed tonality and handedness of camera negatives. Talbot's photogenic drawing paper served at first, but papers coated with albumen emulsion (Louis Désiré Blanquart-Evrard, 1850) displaced Talbot's *salted paper prints*. Silver images suffer from sulfiding, causing them to fade, but gold-toning (1855) mitigated the deterioration, and *albumen prints* remained the chief photographic medium until 1895.

Since speed is not paramount for printing positives, substances less sensitive to light than silver salts were employed in the quest for image permanence. Following the discovery of dichromates (Louis Nicolas Vauquelin, 1798), their light-sensitivity on paper (Mungo Ponton, 1838) led to light-hardening of dichromated gelatin (Talbot, *photoglyphic engraving*, 1852). The addition of artists' pigments to the gelatin matrix, as inert image substances, permitted the development of the *carbon process* (Alphonse Louis Poitevin, 1855; Adolphe Fargier, 1861; Sir Joseph Wilson Swan, 1864).

In 1842, Sir John Herschel discovered that iron (III) citrate was light-sensitive and could yield images in gold, silver, mercury, or Prussian blue—the *cyanotype* or blueprint, the first reprographic process. William Willis patented the analogous platinum process in 1873, and by 1900 his company's *platinotype* paper dominated the market. But demand for platinum as a catalyst in the growing chemical industry brought steep price rises; moreover, the introduction of roll-film cameras, whose small formats required enlargement onto the much faster silver-gelatin development papers, made platinotype commercially unviable by the 1930s. It remains today, together with carbon printing, a minority fine-art practice, yielding images of archival permanence. For the remainder of the twentieth century, silver-gelatin enlarging papers became the commercial norm.

Photography in natural colors was first achieved by James Clerk Maxwell (1831–1879) in 1861, using optical filters to separate three primary colors and to synthesize them additively. Ducos du Hauron published details of a three-color subtractive process, *heliochrome*, in 1869. Gabriel Lippmann, who received the only Nobel Prize (physics, 1908) awarded for photographic innovation, devised a unique interference system for recording color photographs in 1891. More successful commercially was the additive *autochrome* process of the brothers Auguste and Louis Lumière (1907), which used a mixture of starch grains dyed with three primary colors to filter the light falling on a panchromatic emulsion. Color photography progressed with research in synthetic organic chemistry of dyestuffs, notably at the Eastman Kodak Company, which produced Kodachrome in 1935: a triple-layered silver emulsion, sandwiched with subtractive primary dyes.

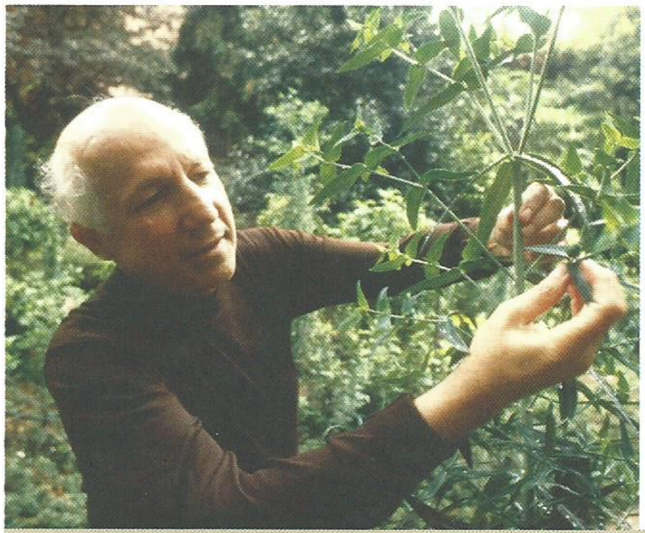
The scientific value of photography for faithful analogue recording is self-evident; further, by disclosing information imperceptible to the eye, photography permitted new discoveries. Early examples include the "chronophotographic" studies of animal and human locomotion (Eadweard Muybridge and Etienne-Jules Marey, 1870s); recording of shock waves (Ernst Mach, 1884); high-speed photography by stroboscopic flash (Harold Eugene Edgerton, 1932); and time-lapse photography (John Ott, 1940s).

The ability of photography to accumulate a weak optical signal over time makes its enhanced recording sensitivity particularly valuable to astronomy and optical spectroscopy. By photographically recording galactic spectra, Edwin Powell Hubble (1889–1953) discovered in 1929 the "red shift," which implied that the universe was expanding. The response of photographic emulsions to X rays has found applications since 1895 in medicine and forensic science. The X-ray diffraction patterns for elucidating crystal structure, and electron diffraction patterns from gaseous molecules, were first recorded photographically. Antoine Henri Becquerel owed his discovery of radioactivity in 1896 to the sensitivity of emulsions to charged particles; the ensuing technique of *autoradiography* finds application in biological studies and metallographic analysis. Emulsions can register the trajectories of cosmic rays, and particle physics employs photography to record events in its cloud and bubble chambers.

With the advance of modern electronics, photoelectric devices are replacing silver-gelatin emulsions. Digitally-processed electronic imaging has reduced the role of photography in science and the lens-based media. Yet the photograph will endure in the art and archives of humanity.

MIKE WARE

PHOTOSYNTHESIS, the metabolic reactions that provide plants with a source of food, is usually referred to as fixing energy (light) from the sun in the form of carbohydrates. The term dates from 1893, when the major steps in the process were identified. Before then, by analogy with animals, most philosophers regarded plants as breathing organisms deriving their nutrients from water and the air alone. During the seventeenth and eighteenth centuries plant physiology became a branch of pneumatics. Stephen Hales, who first recorded the exchange of gases, believed that plants "perspired" during the day and "imbibed" at night. These ideas encouraged the suggestion that plants transformed stale air into fresh or sweet air and led Georg Ernst Stahl and then Joseph Priestley and others to identify the gases involved. Priestley provided evidence that green plants produced dephlogisticated air, the air that Antoine-Laurent Lavoisier redefined as oxygen (1777). Jan Ingen-Housz saw this process as a necessary counterpart to the respiration of animals. Air spoiled by the breathing of animals served as a kind of food for plants, and plants in turn supplied animals with purified air. These reciprocal actions constituted a cycle, demonstrating the economy of nature.

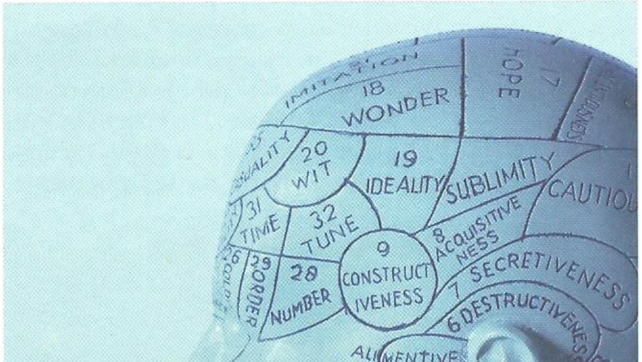


Biochemist Melvin Calvin (1911–1997) received the Nobel Prize in Chemistry in 1961 for identifying the path of carbon during photosynthesis.

Ingen-Housz regarded the cycle, which he described accurately, as convincing evidence of the handiwork of the creator. From 1772, Lavoisier developed the theory that combustion arose from or in the fixation or combination of oxygen in the air with any burning substance. Light and heat appeared as a result. Lavoisier later proposed that the oxidation of the carbon in food produced fixed air (carbon dioxide). The presumed goodness and efficiency of cyclical exchanges of gases, which appealed to religious sentiment as well as to reason, provided a strong basis for future research. In essence, the eighteenth century had demonstrated that plants remove carbon from atmospheric carbon dioxide and release oxygen back into the atmosphere.

With the shift in interest toward cellular activities in the nineteenth century, research began to center on the mechanisms by which plants captured carbon from the air, although only toward the second half of the century was the extent to which plants synthesize the greater part of their substance fully appreciated. Investigators soon recognized the role of light and the significance of the green pigment (chlorophyll). Julius von Sachs established the sites for absorption of gases in leaves and the biochemical pathways leading to the formation of starch and other substances. He demonstrated that the starch usually present in green cells came from the carbon dioxide absorbed and decided that starch was the primary substance produced by photosynthesis. Following up Sachs's theory, researchers discovered that starch makes up only a by-product of the assimilation process.

Subsequent investigation showed that carbon dioxide must combine with chlorophyll before chemical reduction takes place in a number of steps involving oxygen, water, and light. In 1919, Otto Warburg began work to determine the minimum number of photons required to yield a molecule of oxygen. He found it to be close to four. His initiative opened a period of research into the details of primary light conversion using Chlorella, a unicellular green algae, as the experimental organism of choice. The prevailing view that a plant's output of oxygen derived from carbon dioxide was challenged in the 1930s by Rene Wurmser, and then by Cornelius Bernardus van Niel, at Stanford, who claimed that it must come from water. In 1937, Robin Hill in Cambridge confirmed the water origin and pointed to chloroplasts as the active sites. During the 1940s Melvin Calvin and his group at Berkeley worked out dark reaction sequences thanks in part to the availability of radioactive Carbon 14 and improvements in chromatography. Calvin received the Nobel Prize in chemistry in 1961 for unraveling the path of carbon in photosynthesis. Another member of Calvin's group, Daniel Arnon, established definitively that isolated chloroplasts could perform all the responses associated with photosynthesis.



Phrenology divides the skull into areas associated with various aspects of personality and evaluates the character of an individual by the bumps and hollows.

In photosynthesis, it is now understood that water acts both as a hydrogen donor and a source of released oxygen. Only part of the process depends on illumination. An important development was the recognition that plants do not create the energy stored in their sugars, but merely fix energy radiated by the sun. Andreas Franz Wilhelm Schimper's discovery that starch stores energy allowed scientists of the early twentieth century to discuss the circulation of energy through the natural world in biochemical terms, as the synthesis and subsequent breakdown of carbohydrates and other vegetable products. From the 1960s, understanding of photochemical action has been enriched by the determination of the detailed molecular processes involved.

JANET BROWNE

PHRENOLOGY AND PHYSIOGNOMY are two methods of studying cranial anatomy as indicative of intelligence, personality, and temperament. Phrenology arose at the end of the eighteenth century, when physiognomy was in decline. Franz Joseph Gall, founder of phrenology, might have been influenced by the physiognomical tradition, but his methodology was based primarily on his own research.

Physiognomy was endorsed by the *Physiognomica,* which circulated in ancient and medieval times under the authorship (now doubted) of Aristotle. Galen connected Aristotelian physiognomy with the humoral theory of health and illness. Prominent Medieval authors developed the subject, which, however, had played out by the eighteenth century. The term "physiognomy" was in use as late as 1834 but began to be supplanted by "phrenology" in 1819.

Gall received his M.D. in Vienna in 1785 and developed a lucrative medical practice. By 1791, he had published his ideas on brain functions, which he concluded were highly localized. Personality traits and abilities supposedly depended on the size of different parts of the brain. He initiated studies on the correlation between structures and functions. However, his evidence was anecdotal, and controversy over his claims drove him to seek evidence in dissections and demonstrations. In 1800, he attracted a disciple, Johann Christoph Spurzheim, who assisted in anatomical researches until they parted company in 1813. During their collaboration they published the first two volumes of Gall's *Anatomie et physiologies du systéme nerveux* (5 vols., 1810–1819). These elaborate studies were intended to illustrate rather than test Gall's system, but they did not convince academic and medical authorities in Paris any more than his earlier research and teachings had persuaded the Viennese. A controversy arose over the grounds for this rejection. Did it have to do with substance or divisions of science? Before Gall began his teachings, brain functions had been explained mainly within philosophy rather than physiology.

Spurzheim traveled to London and in 1815 published *The Physiognomical System of Drs. Gall and Spurzheim.* Gall identified twenty-seven faculties of the mind, and Spurzheim thirty-five. Spurzheim won converts in both London and Edinburgh (where he lectured in 1816), but like Gall failed to win over scientific or medical authorities. Spurzheim died during a successful lecture tour in America in 1832. Gall had died in Paris in 1828.

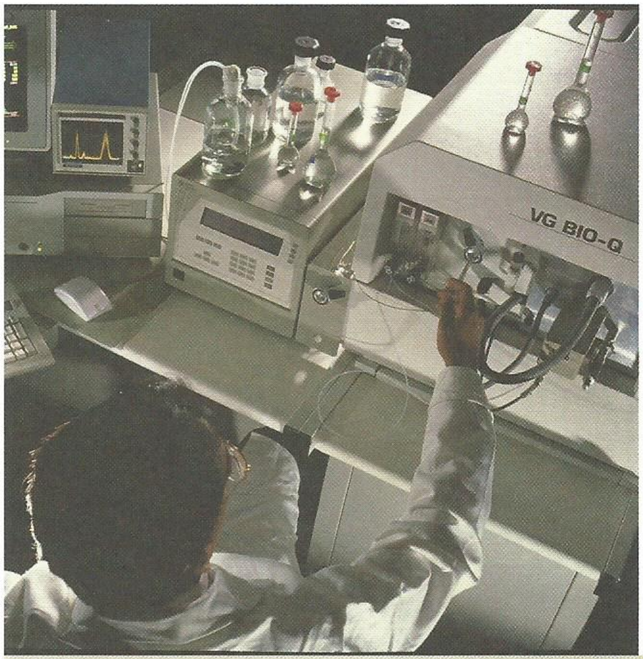
Although Gall and Spurzheim eventually disagreed over details of investigation and interpretation, in general phrenologists used as a reference an anatomical chart of the brain with faculties of the mind labeled on its anatomical parts. The investigator needed to determine the relative size of the different faculties on his subject's brain as visible from the skull. If the subject cooperated, the investigator made careful measurements with calipers and then noted that a given faculty was "very small," "moderate," "full," or "very large." If a subject was uncooperative, an experienced phrenologist could still make a visual analysis reasonably accurately. An expert could do the same with a good portrait or bust.

Spurzheim's most important converts were George Combe, a successful lawyer in Edinburgh, and his younger brother Andrew, the most illustrious British physician to defend phrenology. They organized the Edinburgh Phrenological Society (1820) and founded *The Phrenological Journal* (1823). In 1819, George Combe published his own *Essays on Phrenology,* which he steadily revised and enlarged and eventually retitled as *A System of Phrenology* (5th ed., 1843). He outdid Spurzheim by raising the faculties of the mind to forty-five. Andrew Combe advanced phrenology in a popular textbook, *Principles of Physiology Applied to the Preservation of Health* (1834), which had fifteen editions before his death in 1847. Combe also wrote a best-seller, *The Constitution of Man* (1828).

George Combe acquired a disciple, Hewett Cottrell Watson, an Englishman who went to Edinburgh in 1828 to study medicine and phrenology, which was not taught at Edinburgh University or its medical school. Watson did well in his courses but quit medical school a semester before earning a degree, having decided that he would never practice medicine. Combe respected Watson's abilities, and Watson began publishing in *The Phrenological Journal* in 1829. After leaving Edinburgh, Watson ceased writing scientific articles on phrenology, but remained a staunch advocate. In 1836 he published *Statistics of Phrenology,* which was not a statistical analysis of phrenological data, but an account of progress made in advancing phrenology. In 1837, he became editor of *The Phrenological Journal,* hoping to raise its scientific standards. He wrote lofty editorials, but his criticism and ridicule of articles submitted only aroused the anger of authors, and in November 1839 he resigned. Watson abandoned phrenology and criticized it in correspondence with Combe until Combe died in 1858. The last serious attempt to defend phrenology was W. Mathieu Williams's *A Vindication of Phrenology* (1894).

FRANK N. EGERTON

PHYSICAL CHEMISTRY. The recognition of physical chemistry as a subfield within the broader field of chemistry is usually associated with the founding in 1887 of the journal *Zeitschrift für physikalische Chemie* by Svante Arrhenius in Stockholm, Wilhelm Ostwald in Leipzig, and Jacobus Henricus van't Hoff in Amsterdam. In his account of the history of the discipline, Ostwald rooted its foundations in electrochemistry. Somewhat differently, Walther Nernst, in a speech at his newly built physical chemistry institute in Göttingen in 1896, described van't Hoff's work on dissociation in solutions as the path that reunited the sciences of chemistry and physics in a return to Antoine-Laurent Lavoisier's late eighteenth-century vision of a unified science.



A scientist injects a sample into a Mass Spectrometer, an instrument used for protein analysis, which is used to identify chemical compounds by exploiting the behavior of their molecular ions in magnetic and electric fields.

The phrase "physical chemistry" was much in use before the 1880s, for example, by Robert Bunsen, Hans Heinrich Landolt, and Heinrich Rose, and in the title of the *Annalen der Physik und der Physikalischem Chemie* (1819–1823), which became Johann Poggendorff's *Annalen der Physik und Chemie* in 1824. Hermann Kopp received the first independently named university chair in "physical chemistry" at Heidelberg in 1863. Ost-wald's predecessor Gustav Heinrich Wiedemann set up the first German instructional laboratory for physical chemistry at Leipzig in 1871.

Increased governmental concern in the 1860s to promote scientific and technological progress made expanding resources for scientific education available first in Germany and then elsewhere in Europe and in the United States. Physical chemistry became a supplement to the curriculum in organic, agricultural, and medical chemistry that had been the heart of chemical education in universities since the 1830s.

The areas of study that defined physical chemistry at the end of the nineteenth century were thermodynamics, electrochemistry, colloid and surface chemistry, and chemical spectroscopy. They were enriched during the early decades of the twentieth century by chemical kinetics, electron and quantum chemistry, X-ray crystallography, and new kinds of spectroscopy.

In the 1850s and 1860s, Marcellin Berthelot in Paris and Julius Thomsen in Copenhagen developed theories of chemical affinity based on the assumption that the chemical force (affinity) that holds the parts of a molecule together is directly proportional to the heat evolved during its formation. By the mid-1880s, Pierre Duhem had rejected the Berthelot-Thomsen thermochemical approach. Duhem and others adopted the thermodynamical theories of Rudolf Clausius (1854, 1865), J. Willard Gibbs (1875–1877), and Hermann von Helmholtz (1882) for chemical purposes.

By the late 1880s, a stable chemical system could be defined mathematically as a state of equilibrium in which the entropy (S) of the system had reached a maximum value and the internal energy (U) a minimum. Entropy measures energy unavailable for work and "free energy" (F) the energy potentially available for work, given values for the mechanical equivalent of heat (J) and temperature (T). Thus, $F = U - JTS$; and chemical affinity is identified with free energy or with work, not with heat.

These results, based on precise experimental work, were mathematical and abstract in character. "Energeticists" like Ostwald and Duhem, who opposed the use of visualizable models in science, lauded this new physical chemistry, but mechanists like Ludwig Boltzmann in Austria and Marcel Louis Brillouin and Jean Baptiste Perrin in France preferred descriptions linked to particles in motion and the kinetic theory of gases.

Drawing on the work of Helmholtz and others, van't Hoff demonstrated in his *Etudes de dynamique chimique* (1884) that the work of chemical affinity could be calculated from vapor pressures, osmotic pressure, or electrical work in a reversible galvanic cell. His starting point in reaction velocities made a contribution to chemical kinetics. The everyday use of thermodynamics in chemical work was greatly simplified by Gilbert N. Lewis and Merle Randall's *Thermodynamics and the Free Energy of Chemical Substances* (1924), which embraced Gibbs's expression for free energy at constant pressure rather than Helmholtz's and van't Hoff's expression for constant volume.

Arrhenius took up van't Hoff's application of the ideal gas law to osmotic pressure and dilute solutions in his doctoral dissertation on electrolytic dissociation (1887). Arrhenius made the surprising argument that at infinite dilution, molecules of electrolytes break up into charged ions even in the absence of electrical current. Arrhenius's notion of independent ions built on Helmholtz's suggestion of 1881 that ions produced in electrolysis carry discrete "atoms of electricity" that might be units of chemical affinity attached to elementary substances. The physicalist electrolytic chemistry of Arrhenius, van't Hoff, and Ostwald became known as "Ionist" chemistry.

Nernst served briefly as Ostwald's assistant in Leipzig. Nernst's practical interest in electrical lamps led to his work of the dissociation of gases at high temperatures in addition to his studies of solutions, solids, and surface chemistry. Irving Langmuir, who took his doctoral degree at Göttingen with Nernst and spent most of his career at the General Electric Company's research laboratory in Schenectady, New York, investigated a similar range of subjects, which preoccupied physical chemists in the early twentieth century.

In late 1905, Nernst stated a third law of thermodynamics, which provided the means for calculating values of specific heat and for predicting the likelihood of chemical reactions from recognition that the values of entropy and specific heats approach zero at very low temperatures. Albert Einstein's quantum theory of solids, published in 1907, provided theoretical foundations for Nernst's prediction. The utility of the third law persuaded many physical chemists of the usefulness of the statistical mechanics of Gibbs and Boltzmann, as well as of the quantum theory, in chemical studies.

Optical methods have been consistently fruitful in physical chemistry. Polarimetry resulted from the discovery of Jean-Baptiste Biot and François Arago in 1840 that a monochromatic beam of plane-polarized light is twisted or rotated by solutions of sugar, camphor, or tartaric acid. The new method of study led to the recognition of asymmetries in molecular structure.

Spectroscopy in the chemical context developed from methods used by Robert Bunsen and Gustav Kirchhoff to identify chemical substances by the colors they emit in flames. In 1860, Bunsen and Kirchhoff announced the discovery of cesium, identified by its blue spectral lines; rubidinium followed in 1861, identified by its dark red lines.

In the late nineteenth century, several scientists, including George Johnstone Stoney, Arthur Schuster, and Johann Jakob Balmer, sought quantitative relations among the frequencies of the spectral lines emitted by an element. The first important success, Balmer's formula of 1885, gave the wavelengths of four lines in the visible spectrum of hydrogen in terms of integral whole numbers and a constant. In 1890, Johannes Robert Rydberg revised the Balmer formula by introducing the concept of wave number (reciprocal of the wavelength) in an equation with a constant (Rydberg constant) common to all series and elements.

Max Planck's early quantum theory resulted in a new understanding of the meaning of spectra. Heinrich Kayser incorporated Planck's radiation formula into the second volume of his *Handbook of Spectroscopy* in 1902. Niels Bjerrum interpreted spectra in terms of quantum theory in 1911, and Niels Bohr combined spectroscopic data with the quantum hypothesis in his revolutionary paper of 1913 on the hydrogen atom's electron energy.

Gerhard Herzberg's *Atomic Spectra and Atomic Structure* (1936) became one of the fundamental reference books for chemical applications of spectroscopy. By the 1950s, laser spectroscopy, nuclear magnetic spectroscopy, and other new techniques came to supplement visible, infrared, and Raman spectroscopy, the latter a technique discovered by C. V. Raman and K. S. Krishnan in 1928 for studying molecular structure based on the scattering of a beam of monochromatic light.

Mass spectroscopy, developed by Francis Aston and other physicists beginning in the 1920s, enabled chemists to sort out isotopic and molecular weights. The various spectroscopies not only identified elements and compounds, but also indicated submolecular structures, steric alignments, and bond angles.

By the 1920s, X-ray diffraction was employed to study the organization of atoms and submolecular units within molecules. Supplemented by electron diffraction after 1930, it helped to map the structure of metallic alloys, textile fibers, rubber, and large biologically significant molecules like proteins, nucleic acids, and vitamins. These methods had enormous industrial and commercial application as well as importance in fundamental research.

Paul A. M. Dirac, Max Born, and other physicists liked to say that quantum mechanics reduced chemistry to physics. Most chemists disagree. Physicists and chemists equally contributed to the development of quantum chemistry. Among the physicists, Walter Heitler, Fritz London, Friedrich Hund, and John Slater made notable contributions. But not until 1931, when Slater and Linus Pauling developed methods to explain directed chemical valence, did a truly chemical quantum mechanics exist. Their atomic orbital method was largely supplanted in chemical practice after the

1950s by the molecular orbital method developed simultaneously through the work of Hund, Erich Hückel, and, notably, Robert Mulliken.

Chemical kinetics, like quantum chemistry, became an increasingly sophisticated mathematical subject after World War I. Interest in chemical kinetics revived in the 1920s over the question whether activation energy for monomolecular reactions came from radiation or molecular collisions. Farrington Daniels, Hugh S. Taylor, and Cyril Hinshelwood developed evidence and theories for the collision hypothesis in the late 1920s, which replaced the radiation theory defended by Jean Perrin and others at the beginning of the decade. In the 1930s, Michael Polányi and Henry Eyring formulated a generalized transition-state theory for elementary chemical processes.

In the study of chemical kinetics in the late twentieth century, physical chemists employed not only the bulk experiments traditional to their field, but also molecular beams in which lasers excite reactant molecules into desired vibrational and rotational states and chemists identify the states of the products by their fluorescence. Dudley Herschbach and Yuan Tseh Lee pioneered this work.

In the development of physical chemistry, both physicists and chemists played important roles, with their work identified as chemical physics, theoretical chemistry, or theoretical physics as well as physical chemistry. The foundation in 1933 of the *Journal of Chemical Physics* marked a breakthrough in the United States for the application of sophisticated mathematical theories, including quantum mechanics, in chemistry. The journal's first volume included papers from Eyring, Herzberg, Mulliken, Pauling, Slater, and Taylor. What has most distinguished late twentieth-century physical chemistry from its late eighteenth-century counterparts have been innovations in instrumental practice and sophistication in mathematical theory.

MARY JO NYE

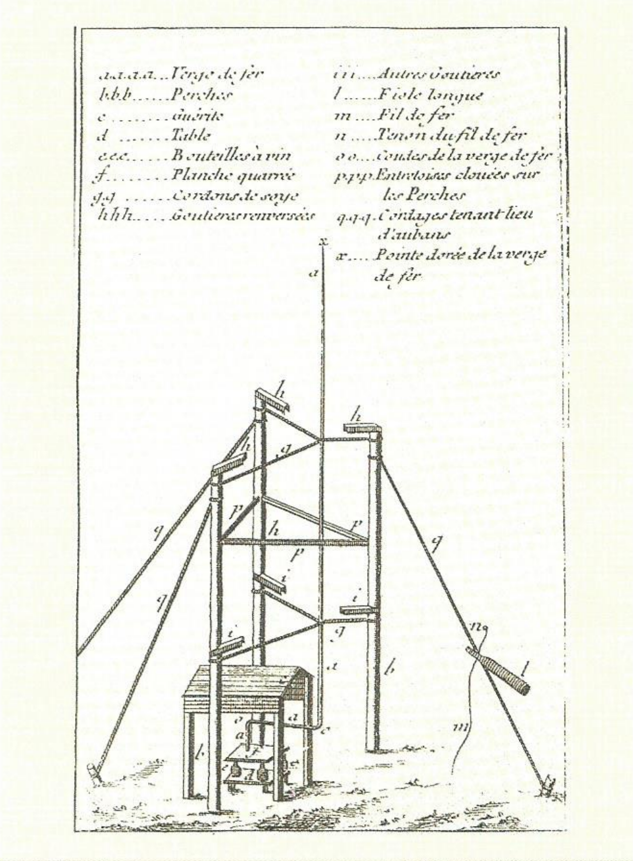
PHYSICS. The development of physics provides a particularly strong example of the evolution of natural knowledge into modern physical science. Its traditional meaning of systematized, bookish knowledge about the entire physical world persisted until the eighteenth century; as late as 1798 the Académie Royale des Sciences of Paris could announce, as the subject of a prize competition in physics, "the nature, form, and uses of the liver in the various classes of animals." To be sure, the assumptions behind the question differed in an essential respect from the implications that would have been drawn a century or so earlier, when "physiologia" was often used as a substitute for "physica." This essential difference was the expectation that competitors would base their answers on experiments, at least some of which they would perform themselves.

Around 1800, "physics" in its old, inclusive sense, modified to imply experiment and some measure of research, lost out to a new division of science bearing the same name. This decisive historical fact is often veiled by the use of "physics" to refer to natural knowledge through the ages. The new physics of 1800 restricted itself to the inorganic world and, within it, to subjects open to investigation by such instruments as the air pump, electrical machine, balance, thermometer, and calorimeter. In place of the organic world, physics took on subjects previously the property of mathematics, especially mechanics and optics, and strove to quantify the fields that had distinguished physics during the eighteenth century: electricity, magnetism, heat, and pneumatics, which had garnered attention as particularly suitable for catchy demonstration experiments to large and varied audiences.

The leaders in this reformulation are often grouped together as the school of Pierre-Simon de Laplace. They applied the mathematical approach developed for the theory of gravity to imponderable fluids supposed responsible for the phenomena of heat, light, electricity, magnetism, fire, and flame. The scheme of imponderables was unified by this common approach; but each fluid functioned independently and irreducibly in its theory. Neither the fluids nor the forces they were supposed to carry linked to one another in any fundamental or ontological sense. Rather, the Laplacian school and its fellow travelers deployed the fluids and forces in an instrumentalist way. It thus promoted the dismemberment of science and the dropping of scruples against instrumentalist mathematical descriptions.

The physics of 1800 differed in scope from later physics by including meteorology and parts of subjects shared with chemistry, like atomism, pneumatics, and thermodynamics. It fell far short of twentieth-century physics in eschewing models of the microworld apart from very general assumptions about the molecular constitution of bodies. A major exception to this generalization was the attachment of atomic weights to chemical atoms. The French-dominated physics of 1800 also differed from physics in 1900 or even in 1850 by having a vigorous opponent, Naturphilosophie, which depreciated mathematics and dismemberment and tried to reintegrate physics on general philosophical principles.

The basis of integration proved to be mechanics, which the Naturphilosophen disliked for its mathematics, strict-


a.a.a.a...Verge de fer
b.b.b......Perches
c........Guérite
d ......Table
e.e.e......Bouteilles à vin
f........Planche quarrée
g.g ......Cordons de soye
h.h.h.....Gouttières renversées
i.i.i....Autres Gouttières
l......Fiole longue
m....Fil de fer
n....Tenon du fil de fer
o.o...Coudes de la verge de fer
p.p.p.Entretoises clouées sur les Perches
q.q.q.Cordages tenant lieu d'aubans
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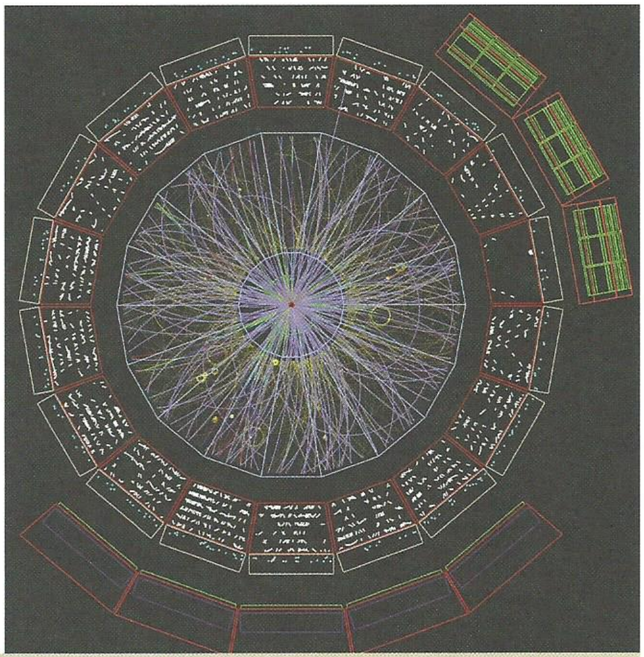
The set-up used by François Dalibard in 1752 to test Benjamin Franklin's conjecture that lightning is an electrical phenomenon. From B. Franklin, *Expériences et observations sur l'électricté*, tr. F. Dalibard (1756), and G. Dary, *A travers l'électricité* (1900).



Simulated computer display of a particle collision in the large hadron collider at CERN (the European particle physics laboratory) near Geneva, Switzerland

ness, and sobriety. This integration, which characterizes the so-called classical physics of the later nineteenth century, began around 1800 with the renewal of a quantitative wave theory of light. By 1840, most physicists (to use a word then just invented) associated light with the vibrations of a world-filling ether conceived as a medium obeying the laws of mechanics. That substituted a mechanical system for the imponderable fluid of light. As this conception crystallized, the fluid of heat vaporized; by 1860, the mechanical theory of heat and the kinetic theory of gases had replaced the old imponderable caloric. This process brought two fundamentally new concepts and techniques into physics: statistics, in the form of probability calculations about the herd behavior of molecules, and irreversibility, in the form of the thermodynamic quantity entropy.

That left the electrical and magnetic fluids, four in all, a positive, a negative, an austral, and a boreal. The discoveries of connections between electricity and magnetism beginning in 1820 led to the representation of magnetism as electricity in motion, a development completed by the demonstration of their identity in the theory of relativity. Thus, by 1860, the main imponderables of 1800 had either vanished altogether (caloric and the magnetic fluids), metamorphosed into a mechanical system (light), or remained with enhanced properties (electrical fluids). A further diminution occurred with the unexpected discovery that electromagnetism could be represented as a disturbance in the same ether whose vibrations made up light, or, stated phenomenologically, that light and other radiations were manifestations of electromagnetism, a representation confirmed by the production of radio waves in 1887.

Since the ether had been understood as a mechanical medium, physicists, particularly those trained at the University of Cambridge, tried to model electromagnetic phenomena in mechanical terms. It remained only to bring matter into the system. A way opened with the discovery that whirlpools or vortex rings in a fluid with the sorts of properties usually ascribed to the ether would last forever. These rings could link and separate in accordance with other goings-on in the ether; in short, they could behave in many ways like chemical atoms. Thus arose the grand and remote program of complete mechanical reduction, which few physicists, perhaps, expected to see realized.

The possibility of concocting this program arose from the very substantial progress that mechanics itself had made during the middle third of the eighteenth century. The powerful mathematical theories of the behavior of fluids and solids then developed stood ready for exploitation by theorists of the ether. Also the more general formulations of mechanical principles were extended still further and adapted to electromagnetism and the kinetic theory of heat. The apparent success of the generalized mechanics in describing the phenomena of electromagnetism, light, and heat confirmed the possibility of mechanical reduction without the necessity of exhibiting an explicit model or picture. That was comforting. Of course, the scheme could be turned around and electromagnetism taken as primary. Many distinguished physicists around 1900 played with the idea of electrodynamic reduction.

The extraordinary progress of classical physics was supported by new institutional arrangements that made research as well as teaching the business of professors. The physics research of the eighteenth century, insofar as it existed at all, was primarily an easy-going affair associated with academies. Toward the end of the ancien régime and, increasingly after 1830, individual university professors were conceded the right, and then given the duty, to undertake research, usually at their own expense, as part of their jobs. Their institutions provided space, a collection of teaching apparatus, and perhaps a mechanic to keep it in order. Beginning around 1870, with the foundations of the Cavendish Laboratory in Cambridge and the Physics Institute of the University of Berlin, the idea that a professor's university should furnish him with the instruments he needed and a place to work with collaborators and advanced students steadily gained ground. (Here physics followed chemistry, whose first important university facilities for teaching and research go back to the 1830s.) The instruments employed in the institutes at first were largely home made. By the end of the century, however, most of the important equipment—electrical parts, air (or vacuum) pumps, refrigerators, batteries—came from commercial suppliers.

The recognition of the need for institutionally supported research both to advance science and to train students owed much to the demands and opportunities of the new electrotechnology and the perceived need to give doctors, engineers, and science teachers a grounding in physics. By 1900, every major university and higher school in Europe and the United States had a physics institute. By far the largest output of papers on physics came from academics. Most of them worked in Britain, France, Germany, or the United States, which then were investing the same proportion of their gross domestic product (GDP), and enlisting the same proportion of their populations, in the physics enterprise. An example of their investment, and an indication of the widening of occupational opportunities beyond the universities, was the establishment of national (or, in the case of France, international) bureaus of standards.

This enterprise reached a climax in the symbolic year 1900, when the world's physicists gathered in Paris for their first and last general conclave. They then awakened, as one participant said, to the news that the keystone of their grand synthesis might have been found. This was the electron, which, it appeared, might be the unique building block of both matter and electricity, the clue to chemical binding, the explanation of the ion, and the root of X rays and radioactivity. These considerations inspired the design of several model atoms based on electromagnetic theory. None worked well beyond the limited range of the phenomena for which it was devised, for example, magneto-optic effects and the scattering of rays from radioactive substances. Until around 1910, all these models lacked a principal ingredient that would make the theory of atomic structure into the leading sector of physics in the 1920s. The necessary ingredient was the quantum, introduced into the theory of black-body radiation in 1900. Its fundamental importance for physics had only just been recognized when the world's physicists flung themselves into world war.

The performance of physicists during World War I demonstrated their indispensability to modern society. New forms of government, foundation, and philanthropic support became available for scholarships, fellowships, and research. The worldwide activities of the Rockefeller Foundation were especially fruitful, since it favored the transfer of quantum physics from Europe to the United States and of American instrumentation, particularly cyclotrons, abroad. Basic physics, having finished provisionally with radiation and atoms, delved into the nucleus; here the United States, with sizable disposable income despite the depression, led the way into big science. American physics strengthened further as a result of the emigration of European refugees driven from their positions by fascist regimes. Nazi science policy stultified fundamental physics, in which Jews had been disproportionately prominent, in Germany and its occupied territories. As Germany declined, Japan and the Soviet Union developed their own capacities for training advanced students and set up research institutes often with liberal funding from military or industrial sources. The Soviet capacity centered on the institutes of the Akademiia nauk (Soviet Academy of Sciences) and laboratories supported by the Commissariat for Heavy Industry; the Japanese, on the imperial research institute RIKAN.

As physics spread geographically it also spread intellectually to territory newly conquered by the quantum. The study of cosmic rays, the behavior of bodies at low temperatures, the solid state, and the nucleus advanced prodigiously during the 1930s. The ascendancy of the electron was challenged or shared by the deuteron, meson, neutrino, neutron, positron, and proton. Molecular physics began to yield to new methods of calculation. Machines and ideas spun off into neighboring and even distant sciences, for example, astronomy (e.g., stellar energy) and biology (e.g., radioactive tracers). The principles of complementarity and uncertainty, invented to domesticate a mismatch between ordinary intuitions and the formalism of quantum mechanics, found applications to vitalism, psychology, philosophy, and theology.

Despite cries for a moratorium on research and movements for social responsibility among scientists, which gained some strength during the depths of the depression, the public applauded the science-based luxuries it soon found to be necessities: commercial radio, the all-electric kitchen, the long-distance telephone, air mail, air travel, and, above all, the automobile. As this easily extendable list suggests, the public did not (and does not) distinguish between science and technology. The confusion was compounded by the multiplication of industrial research laboratories, some of which, especially in the United States, permitted their technical staffs considerable leeway in choice and conduct of research. These laboratories helped to keep up demand for physicists so that, except for the loss of a year or two's crop of new graduates, the depression had no effect on recruitment, at least in the United States.

The demand became so great during World War II that physics students who had not completed their degrees were employed on advanced research projects. Once again physicists proved their value: operations research, radar, the proximity fuse, cryptography, and the atomic bomb. The great winner in the conflict, the United States, rewarded its physicists after the war by supporting them in the manner to which they had become accustomed. The infusion of public dollars, intended to keep scientists well disposed toward government, as well as to encourage work related to weaponry, exaggerated a style already characteristic of American science: pragmatic, instrumentalist, democratic, and gigantic. The combination proved potent; countries that wanted to compete had no option but to submit to Americanization, especially in the world's most prestigious science, high-energy physics.

The United States assisted participation and competition by helping in the recovery of science in Germany (after picking some plums in Operation Paperclip, in Japan (after throwing its cyclotrons into the sea), and in Europe (by validating CERN, the Centre Européen pour la Recherche Nucléaire, which brought together nations no longer able to compete alone). The recovery called into existence new mechanisms of national support and international collaboration. As a result, Europe and Japan caught up with, and even outpaced, the United States, which, by canceling the Superconducting Super Collider in the 1990s, showed that it no longer had the will, if it had the means, to dominate the world in high-energy physics.

While the particle physicists enjoyed their limelight, their colleagues working on a smaller scale discovered or invented things of greater importance to the public than strangeness, parity nonconservation, the Eight-Fold Way, or the unification of the fundamental forces except for gravity. Radar technologies helped academic laboratories to produce the laser and airports to handle jet-setters. Research into the solid state returned with silicon chips, the computer, and high-temperature superconducting magnets. Color television, direct-dial international telephony, satellite communications, modern banking, the credit card, and so on, demonstrate that physics warmed by cold war can do wonders.

The wonders have included nuclear power and therewith the pollution that arises from the spent fuel and radioactive parts of reactors, which began to spread worldwide in the late 1950s under the American program, Atoms for Peace. The pollution, as well as the involvement of physicists and other scientists in advanced weapons projects, fuelled an antinuclear movement and wider attacks on science. The end of the cold war redirected some of this sentiment against the diffusion of high-tech industry to developing countries. Nonetheless, the spread of Western science, which began before World War I in the colonies of the European powers and produced important indigenous physics communities in the Soviet Union and Japan before World War II, continued into Latin America, the Near East, and continental Asia after 1945. An example of this diffusion of postwar physics, American style, is the synchrotron completed in Brazil in 1996.

The spread of physics to new cultures had a parallel within the old physics-producing countries in the increasing inclusion of groups whose participation had previously been marginal or restricted. Anti-Semitism lost its force in most of the world. Women gained easier access to training and employment. Opportunities were extended to minority groups. Acquaintance with physical principles or gadgetry diffused widely in the general culture along with the computer, high-tech weapons, and space exploration.

On the intellectual and rhetorical side, physicists provided many good accounts of their progress toward a Theory of Everything.

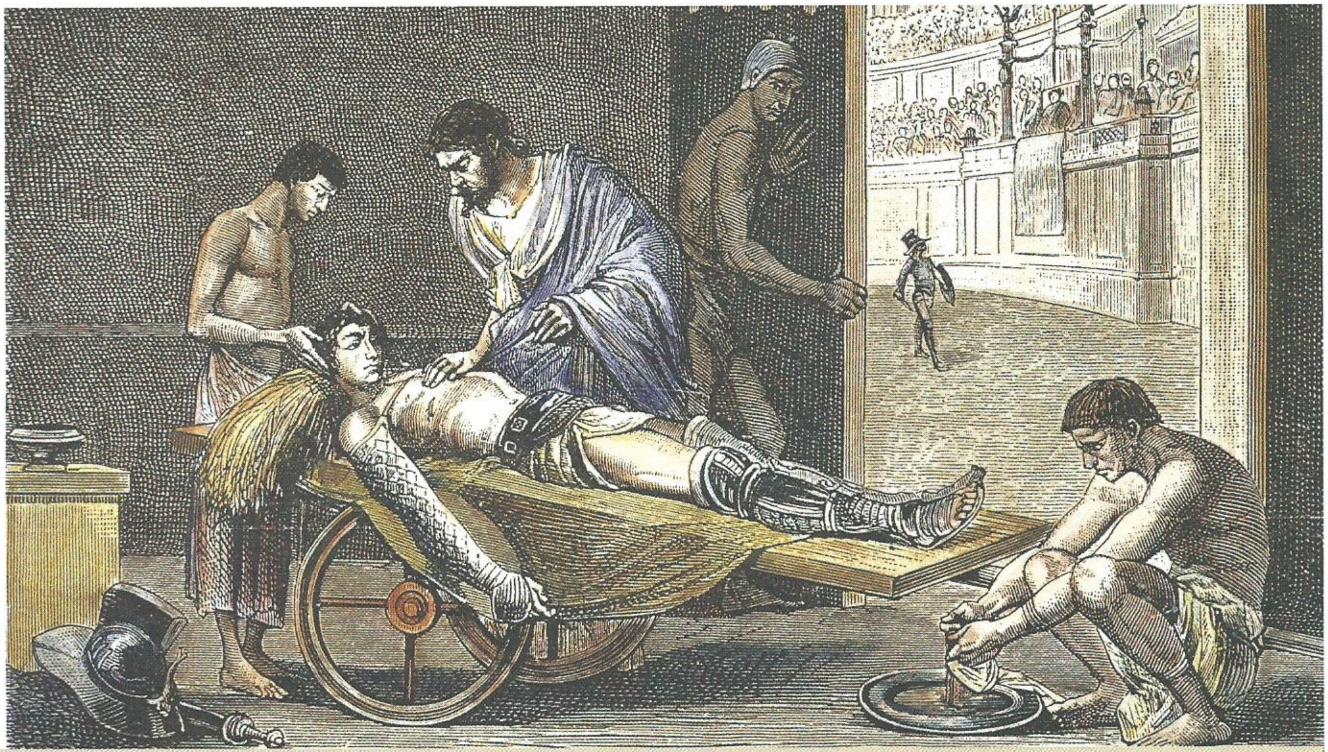
The possibility of an encompassing and final theory arose at the intersection of cosmology and particle physics. Theories of the largest and smallest structures in the universe combined to make a Big Bang. Crucial evidence favoring the doctrine came from the characteristic postwar specialty, radioastronomy. The doctrine of the Big Bang and the expectation by some theoretical physicists that a complete and unified theory of the physical world might be achieved during their lifetimes provoked the interest of diverse theologians and the Vatican. In a limited region of vast extent, therefore, physics has returned to the sort of questions with which its predecessor, natural knowledge, had been engaged.

J. L. Heilbron

PHYSIOLOGY. Originally synonymous with natural philosophy, physics, or the study of all natural bodies, the word "physiology" began to restrict its scope to the structure and composition of the human body during the sixteenth century. The French physician Jean François Fernel then defined physiology as one of the five parts of medicine—the one that "explains the nature of the healthy man, all of his faculties and functions." Fernel contrasted physiology particularly with "pathology," summarized as "the study of the illnesses and affections that can happen to man."

As the study of the structure and functions of the human body, physiology is one of the oldest fields of natural inquiry and links with fewer breaks than almost any other modern science with its roots in classical Antiquity. From Aristotle to Galen, the ancient tradition thoroughly mapped out the internal anatomy of animals closely related to humans and established the principle that the form of the parts must be related to their function. That principle has framed and guided physiological investigation ever since.

Physicians and natural philosophers of the sixteenth and early seventeenth centuries inherited an account of the functional organization of the human body based mainly on Galen. Filtered through twelve centuries and multiple layers of commentary and condensation, the complex, evolving, sometimes contradictory views of the voluminous Galenic corpus have been reduced to an easily remembered system. Despite subtle errors owing to Galen's projection of the anatomy of the apes he had dissected onto the human body he was not permitted to cut, the functional arrangements of the skeleto-muscular system had been thoroughly worked out with only secondary changes into early modern times. The system divided the body into three regions. In the uppermost of these, the head, resided the brain, the "domicile of the human spirit, the seat of thought and reason, and the source and origin of all movement and sensation." Galen had worked out the gross anatomy of the brain, the cranial nerves emanating directly from it, the spinal cord, and the peripheral nerves in considerable and mostly accurate detail, and established regions innervated by various nerves through vivisection experiments not surpassed until the nineteenth century. The heart and lungs dominated the central region, or thorax. The heart was connected with two sets of vessels: on the right side to the veins, through which nourishment, transformed to blood in several stages, most notably in the liver, flowed to all parts of the body; and on the left side to the thick-walled arteries, which also distributed blood, but of a brighter, more spirituous nature, imbued in the left ventricle with vital spirit. The lower region, or venter, was filled by the organs of digestion, through which food passed from the mouth, converted gradually, by a process known as coction, into



Artist's conception of the Greek physician Galen (2nd century A.D.) ministering to gladiators wounded in the arena at Pergamum.

the uniform milky chyle absorbed through the portal veins into the liver. These arrangements provided a well-integrated, comprehensible account of the relation between the observed internal structure of the human body and the primary functions essential to life, and adapted well to explanations of the humoral imbalances associated with disease.

An engineer, however, would have found some difficulties in this account. The Galenic system sometimes required fluids or pneuma to flow both ways in the same vessels, and even to pass the wrong way through valves in the heart generally understood to permit them only to move in the contrary direction. The Italian anatomist Realdo Colombo contended in 1559 that the heart did not attract blood into its ventricles in its expansion, as Galen had said, but pressed it outward in contraction, so that the arteries dilated when the heart constricted; and that the blood did not pass from right to left ventricle through pores in the septum between them, as Galen had said, but by a less direct route through the lungs. More than half a century later the questions Colombo had raised about the motions of the heart and its relation to the motions of the arteries remained controversial.

Through exquisite observations on different classes of animals, especially on the hearts of cold-blooded and dying ones, William Harvey settled to his satisfaction that Colombo's interpretation of the motions of the heart was correct: that through its active contractions it moved blood from the veins into the right ventricle, from there through the lungs to the left ventricle, and then into the arteries, which it filled, "as my breath in a glove." As soon as Harvey asked himself the further question, how much blood does the heart move in this way, he entered a pathway "so new and unheard of" that he feared "every man almost will become my enemy." No matter what quantity of blood he assumed to be driven out of the heart at each beat, the amount that passed through in an hour or a day was so abundant that it could neither be consumed in nutrition nor replenished from the food. The heart must, therefore, produce a "perpetual circular motion of the blood."

Although he did encounter some fierce resistance, Harvey prevailed over his opponents so quickly that within his own lifetime he was heralded as the founder of a new era in medicine. The discovery of the circulation not only ended centuries of domination by ancient systems of thought, but stimulated observations and experiments that brought further novelties, such as the discovery of the lacteal vessels by Jean Pecquet and a sustained collaborative effort by followers of Harvey informally associated at Oxford to understand the relation between the circulation of the blood and the process of respiration.

Harvey himself had examined physiological questions within an Aristotelian philosophical framework, which his successors soon abandoned for the newly dominant mechanical philosophy. That transition wrought a fundamental change in the relation between the living and the nonliving worlds. Where Aristotle had extended to all of nature the purposefulness evident in vital processes and activities, the new mechanical world eschewed teleology. Henceforth those who attempted to understand the underlying physical phenomena taking place in humans or other living things had the choice among explaining them in terms of the shapes and motions of the ultimate particles of matter (later also of the forces exerted between them), invoking recently discovered chemical properties (such as acidity and alkalinity), and referring vital phenomena to principles unlike those of the physical world.

The chemical and physical tools available in the seventeenth and eighteenth centuries had little capacity to explain physiological phenomena. Explanations of the formation of secretions in the salivary glands, the pancreas, or the kidney tubules remained at the level of crude images of particles of the blood that fit into holes in sieves passing through them into the secretory ducts. The new physical concepts did, however, offer more effective means to investigate the circulation, the one system in the body that seemed clearly accessible to mechanical analysis. The influential "iatromechanist" Giovanni Alfonso Borelli was the first person to attempt to determine the force exerted by the heart. The fantastically large number at which he arrived in 1678 stimulated others, such as Newton's follower James Keill, to seek more direct means to measure the force. The lack of agreement among the measurers prompted the famous measurements of the pressure in the arteries and veins that the Reverend Stephen Hales carried out early in the eighteenth century by inserting long vertical tubes into the opened blood vessels of horses and other large animals. When the medically trained mathematician Daniel Bernoulli produced a landmark treatise in 1738 that defined a new field of hydrodynamics, he quickly applied the theoretical principles and methods of calculation that he had introduced there to the study of the heart and movements of the blood.

In 1747, the Swiss professor of anatomy, surgery, and medicine at the University of Göttingen, Albrecht von Haller, published a textbook titled *First Lines of Physiology,* followed between 1759 and 1776 by an eight-volume *Foundations of the Physiology of the Human Body* that summarized and organized all previous work on its structure and functions. These massive works, which Haller intended both to teach medical students the fundamentals of the subject and to open the way to further discoveries, made physiology visible for the first time as a coherent discipline. Also a prolific experimentalist, Haller used the microscope effectively to study the circulation of the blood in the smaller arterioles and veins, and established through numerous experiments a distinction between the sensible parts (nerves) and the irritable parts (muscles) of the body. He met challenges by multiplying his own experiments and by gathering a group of followers who extended the scope of his generalization. He and his followers created an investigative field and raised the standards both for performing and reporting physiological experiments.

By the beginning of the nineteenth century, the physical sciences were supplying new, powerful methods for the investigation of physiological problems. The effects of the advances in chemistry can most easily be seen in the study of digestion. The eighteenth-century investigators René-Antoine de Réaumur and Lazzarro Spallanzani had demonstrated through experiments on various animals that foods are softened into a uniform semifluid mass during digestion, and managed to duplicate the process outside the body with gastric juice withdrawn from the stomach. Chemically, however, they could only say that the process resembled the action of an acid on a metal. During the 1820s, Friedrich Tiedemann and Leopold Gmelin used a repertoire of reagents and extraction procedures to identify the changes that foodstuffs undergo in their passage through the stomach, intestines, and lacteal vessels. Although the only definite chemical transformation they could identify was the conversion of starch to sugar, their investigation opened a continuous tradition that lasted into the twentieth century.

Between 1800 and 1810, a group of physiologists in Paris began to apply the surgical skills acquired during their

Hermann Von Helmholtz (1821–1894) German physicist, anatomist, and physiologist

medical training to make vivisection central to an emerging field in which experimentation was to be not an occasional, but the central activity in the formation of an independent scientific discipline. François Magendie became the most emphatic and persistent advocate for this viewpoint. His own discovery in 1821 of the sensory and motor roots of the spinal nerves became the starting point for mapping the sensory and motor functions of the entire nervous system. His student Claude Bernard, following his lead and succeeding to his chair at the Collège de France in 1855, made between 1848 and 1857 a series of brilliant discoveries, including the action of pancreatic juice on fats, the glycogenic function of the liver, the vasomotor nerves, and the modes of action of carbon monoxide and curare, which made him the most eminent figure of the generation in which physiology became established, both intellectually and institutionally, as the first thoroughly experimental life science.

In Germany, physiology was in the early nineteenth century combined with anatomy in the same university chair. At the Anatomical Museum of the University of Berlin, Johannes Peter Müller represented and actively pursued research in both physiology and comparative anatomy. His *Handbook of Human Physiology,* first published in 1833 and in successive editions until 1844, mastered the field more fully than any physiology text since Haller's. Müller trained students who followed him into each of the fields in which he worked, but none who could command, as he had, their whole range. By the 1840s, advances in both physiology and comparative anatomy made it imperative to separate them, and in 1847 Müller's student Ernest von Brücke accepted, at the Medical Faculty of the University of Königsberg, one of the first independent chairs of physiology. Thereafter such chairs spread rapidly through the major German universities.

Brücke and two other students of Müller, Emil du Bois-Reymond and Hermann von Helmholtz, committed themselves about this time, together with Carl Ludwig, to the goal of reducing physiology to physics and chemistry. This they were never able to do, but they did introduce a style of physiological experimentation based on precise instrumentation, accurate measurement, and rigorous analysis. They sought to examine the magnitude of any observed effect as an unknown function of all the conditions that influenced it and to vary one factor at a time while holding other conditions constant. "The dependence of the effect on each condition," du Bois-Reymond wrote, "can now be shown in a curve, whose exact law, to be sure, remains unknown, but whose course can, in general be outlined." In 1847, Ludwig devised a recording instrument in which the changing magnitudes of a physiological quantity such as the pressure of the blood or the length of a muscle were traced on the smoked surface of a revolving drum, soon known as the kymograph. It quickly became the operational symbol of this mode of functional analysis and a standard fixture in the physiological laboratory of the late nineteenth and early twentieth centuries. The traces recorded by kymographs filled the pages of the journals of physiology.

Meanwhile the advent of the voltaic battery, galvanic currents, and then electromagnetic phenomena had supplied other new tools for physiological experiments. Using a very sensitive galvanometer of his own design, du Bois-Reymond was able to detect, during the 1840s, delicate changes in electric potential accompanying the transmission of nerve impulses in frogs. In 1850, Helmholtz used a ballistic galvanometer to measure the velocity of the nerve impulse itself, a feat once believed to be all but impossible.

By the last third of the nineteenth century, physiologists in Germany possessed large, well-equipped laboratories in which they could not only perform complicated experiments, but train a steadily increasing number of German and foreign students. It was the golden age of physiology. No sooner, however, did physiology attain its autonomy from anatomy than it began itself to undergo a slow process of subdivision. The very tools of the physical sciences that had given it such power early in the nineteenth century now served as foundations for more specialized investigations of the phenomena of life. The first to devolve was physiological chemistry, which attained only two independent chairs in Germany in the nineteenth century, but gave rise in the early twentieth century to the dominant field of biochemistry. The study of the effects of drugs on physiological processes, initiated by physiologists, became by the late nineteenth century the domain of the emerging discipline of pharmacology. What Claude Bernard and others defined in the nineteenth century as "general physiology," or the study of the phenomena of life common to all organisms, became in the twentieth century cell biology. In this steadily expanding array of new biological disciplines, physiology functioned as a mature, or even old-fashioned, science by the middle of the twentieth century. Nevertheless, it has retained domains of its own, such as the regulation of heat, respiration, and other functions, and continues to be an active field of inquiry.

Frederic Lawrence Holmes

PLANETARIUM denotes instruments demonstrating positions and movements of the sun, earth, moon, planets, or stars. Its earliest usage referred to Giovanni de' Dondi's clock and its astronomical dials (around 1360). It later comprised various devices: globe, armillary, equatorium, orrery, grand orrery, compound orrery, tellurian, lunarium, cometarium, jovilabe, Copernican sphere, sphère mouvante, and others. These tools have enabled scholars to pursue research and assisted lay audiences to learn basic astronomy. Since 1923, "planetarium" has connoted an optical projector, its architectural facility, and the facility's institution.

Historical planetaria fall into two categories: illustrations of the celestial sphere and associated daily motions, and representations of longer-term motions and principles pertaining to the classical planets. Instruments of the first category, including celestial and terrestrial globes and many armillaries, served as popular instruments for initial astronomical instruction long after the acceptance of Copernicanism, demonstrating earth-based observations in terms of the celestial sphere, its fixed stars, and imaginary geometrical lines. Important globes include the Atlante Farnese, and models by Ptolemy, Islamic and Chinese scholars, Gemma Frisius, Gerhard Mercator, Tycho Brahe, Jodocus Hondius, Willem Blaeu, Joseph Moxon, Vincenzo Coronelli, and the Cary family. Room-sized hollow spheres by Adam Olearius (Gottorp), Erhard Weigel (Jena), Roger Long (Cambridge), and Wallace Atwood (Chicago) provided experiences of the rotating heavens.

Instruments of the second category featured geared dials, rings, or spheres representing the seven classical planets and, later, the earth and planetary satellites in illustration of Copernican astronomy. Descendants of geared astrolabes and astronomical clocks, significant examples of these instruments include the first known tellurian, by Blaeu, and models by Ole Rømer, Christiaan Huygens, George Graham, James Ferguson, Benjamin Martin, David Rittenhouse, George Adams Sr. and Jr., and William and Samuel Jones, as well as Eise Eisenga's room-sized planetarium. Graham's proto-orrery prompted production of elaborate grand orreries for wealthy patrons and numerous inexpensive models for the adult science education market in Hanoverian England.

Instruments addressing both concepts include astronomical clocks with globes and numerous armillaries enveloping planetary models. Twentieth-century Zeiss optical projection systems synthesize the two categories somewhat, but recent computer-based technology offers more fully integrated illustrations of naked-eye observations and astrophysical principles.

Chicago, New York, Los Angeles, London, Stockholm, Calcutta, and other cities around the world feature public planetaria. School programs account for most visits, particularly in Japan, where Goto and Minolta systems are popular, and in the United States, where many Spitz models were built in response to the *Sputnik* crisis.

At times symbols of city, court, wealth, or learning, planetaria originally conveyed creation's divine order and purpose, providentially extended to human affairs. Enlightenment-era lectures and wealthier homes featured orreries illustrating the solar system's mathematical regularity, whereas early Zeiss shows competed with moving pictures for audiences seeking novel theatrical experiences. Contemporary planetaria proclaim the universe's evolutionary history alongside ever-popular presentations detailing the Star of Bethlehem's astronomy. Controversies over rival goals—education or entertainment—have accompanied planetaria for centuries, a natural consequence of their bridging astronomy and popular culture. The mechanisms of the instruments, the techniques, skills, gender, backgrounds, and communication goals of their artisans and operators, and the desires of their audiences have reflected their cultural contexts throughout the history of planetaria, microcosms of their social and scientific macrocosms.

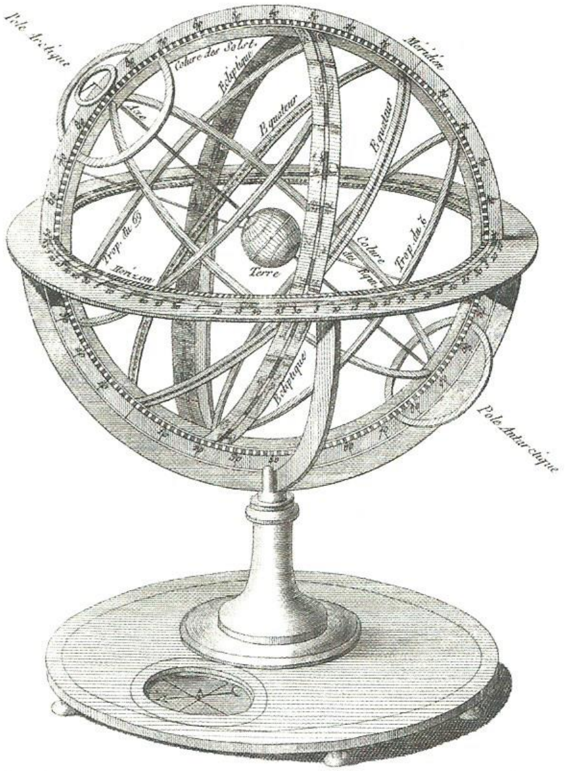
Marvin Bolt

PLANETARY SCIENCE. The term "planetary science" dates from the 1950s. It applies physics, astronomy, chemistry, geology, biology, atmospheric sciences, and oceanography to discrete bodies in the solar system. Previously the study of the planets had been known as "solar system astronomy" or "solar system science." That might have been a better name, because the field takes the whole solar system, including comets, meteorites, asteroids, and planetary satellites as its object of study.

Like the parallel discipline earth science, planetary science emerged in tandem with the new technologies whose development had been spurred by World War II, rocketry and computers in particular. In 1958, the International Geophysical Year began, in large measure to take advantage of these technologies. In the same year the Soviet Union launched *Sputnik* and the space race began. In October 1958, the United States established the National Aeronautics and Space Administration (NASA), to carry on and extend the work formerly done by the National Advisory Committee for Aeronautics (NACA) and other government bodies.

The term "planetary science" first appeared in the journal *Science* in 1959 in a job advertisement put out by the Goddard Space Center. In the same year, the first specialist journal, *Planetary and Space Science,* began publication. In 1962, the American Geophysical Union set up a section

Fig. 1.



The French armillary sphere of the 18th century, can be placed in the plane of the meridian by using the compass in its base.

on planetary sciences. The journal *Earth and Planetary Science Letters* appeared in 1966. Existing institutions like the Houston Lunar Science Institute, university departments, and the journal *Meteoritics* all added "and Planetary Science" to their names.

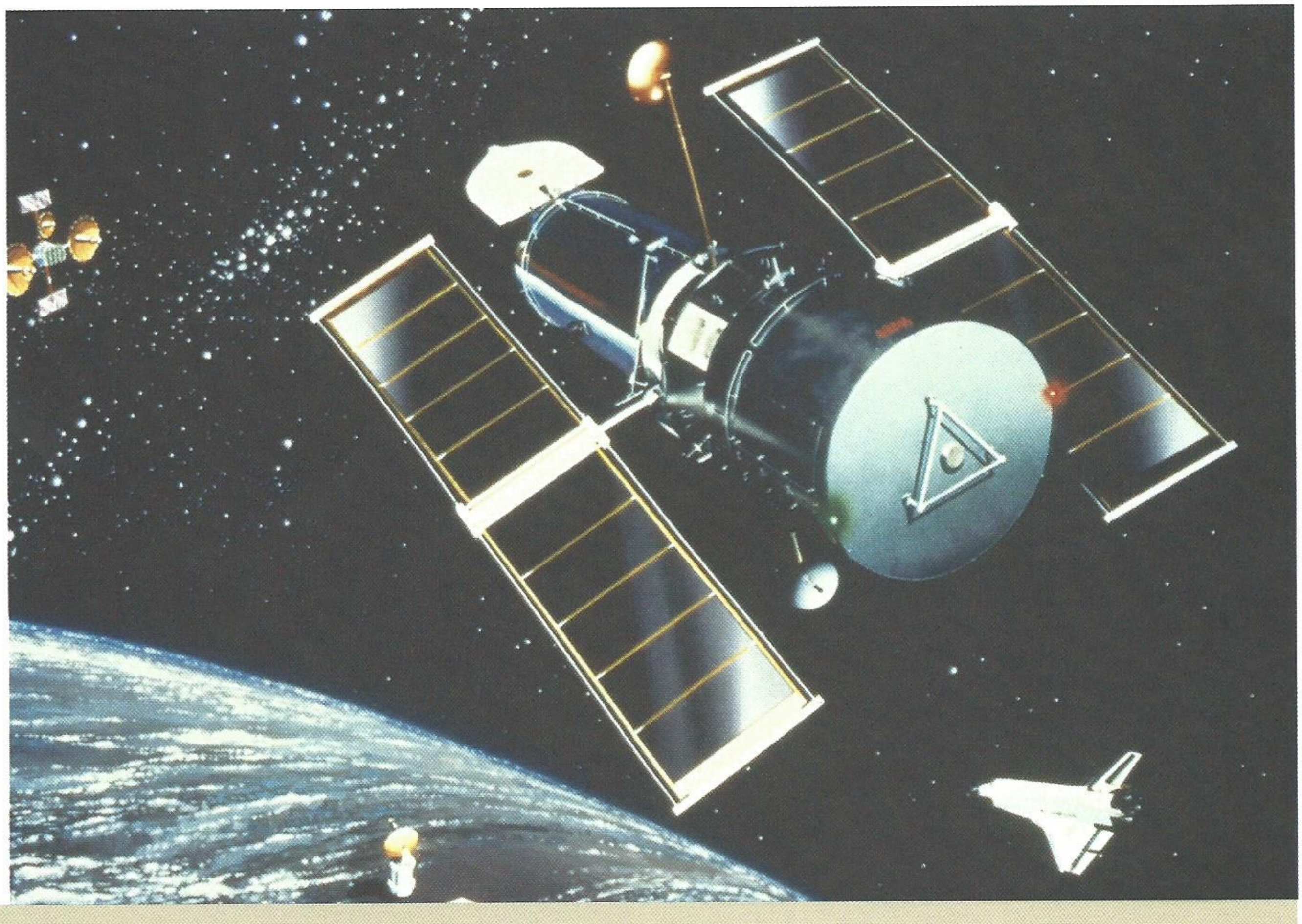
Copernicus, Galileo, Christiaan Huygens, Gian Domenico Cassini, and William Herschel had asked questions about the configuration of the solar system (cosmology), its mechanics, and its origin (cosmogony), and little by little discovered smaller and more distant bodies in the solar system. Galileo, William Gilbert, and Thomas Harriot mapped the Moon in the seventeenth century. Michael Florent van Langren published the first large full-Moon map in 1645, though his projected series of maps showing the Moon in its different phases never appeared in print. The first full-Mars map was published in 1840. The advent of large telescopes and photography vastly improved maps of the Moon and Mars in the remaining years of the century.

Meanwhile physicists, geophysicists, and geologists as well as astronomers pursued many aspects of what would now be planetary science. They asked how the Earth differed from neighboring planets and why. In 1801, the Italian astronomer Giuseppe Piazzi detected the first asteroid. By the end of the century, Maximilian Wolf at the University of Heidelberg had invented a technique for discovering new asteroids by the streaks they left on photographic plates. Astronomers thus discovered the asteroid belt. They also discussed the origin of craters on the Moon and other planetary bodies. In 1803, Jean-Baptiste Biot confirmed that certain stones in Normandy really had fallen from the sky, thus establishing the extraterrestrial origin of meteorites.

After a period in which interest in the solar system waned, two American astronomers, Gerard Peter Kuiper and Harold C. Urey, renewed interest in the subject in the 1940s. Kuiper discovered the carbon dioxide atmosphere on Mars and a disk-shaped region of minor planets (now called the Kuiper belt) outside Neptune's orbit, which he proposed as the source of certain types of comets. He pioneered the development of infrared astronomy, helped identify landing sites for the first manned landing on the moon, and edited two influential works, *The Solar System* (1953–1958) and *Stars and Stellar Systems* (1960–1968). Urey synthesized his investigations of the distribution of elements in the solar system in his *The Planets, Their Origin and Development* (1952).

Since 1960, planetary science has developed rapidly with the help of new optical and radio telescopes. In 1990, the Hubble Space Telescope reached a position high above the distorting effects of the Earth's atmosphere. Project Apollo, which culminated in 1969 with the first human moon landing, the *Pioneer* and *Voyager* spacecraft that explored the Moon and other parts of the solar system, and the *Viking* and *Mars Pathfinder* spacecraft that investigated Mars enabled new kinds of data collection, whether by humans on the moon, by robots on the moon, or by photography and sampling of these and more distant planets. Planetary mapping, aided by radar techniques, proceeded apace. Mercury and Venus, whose surfaces had been difficult to study, Mercury because of its small size and proximity to the Sun, and Venus because of its dense atmosphere, have now been mapped.

New specialties have emerged, such as astrogeology, astrobiology, planetary atmospheres, planetary tectonics, and planetary physics. Topics of active investigation include planetary origins, the structure and composition of plan-



Artist's depiction of the Hubble Space telescope in orbit ets, vulcanism and tectonic activity, the atmospheres and magnetic fields of planets, and the planets of Jupiter. Public interest in planetary science, though not as high as in the 1960s, is still fueled by dramatic photographs, press coverage, and fascination with perennial puzzles like the canals of Mars and the possibility of life elsewhere in the universe. New discoveries and up-to-date information are posted on the NASA site on the World Wide Web. Planetary scientists, who until the end of the second millennium had been concerned almost exclusively with objects within our own solar system, are beginning to pursue the increasing evidence of planets in other parts of the universe.

JOANNE BOURGEOIS

PLASMA PHYSICS AND FUSION. A plasma in physics refers to an ionized gas. Scientists first recognized the importance of plasmas in studies of the propagation of radio waves for the nascent radio industry of the early twentieth century. In seeking ways to send radio signals over long distances they realized that waves seemed to bounce off a conducting layer in the earth's atmosphere, allowing signals to travel far beyond the horizon. One of these researchers, Irving Langmuir of the United States, in the 1920s designated the atmospheric matter "plasma" and investigated its properties in gas discharges in the laboratory.

In the late 1920s, physicists began to apply new theories of atomic structure and quantum mechanics to the energy source of stars. In 1929, Robert Atkinson and Fritz Houtermans predicted that the nuclei of light atoms such as hydrogen, the primary constituent of the sun, could fuse through quantum tunneling, and that the resultant atoms would weigh less than the original constituents. Albert Einstein's mass-energy relation suggested that fusion would release vast amounts of energy, enough to power the stars. Hans Bethe and others developed the theory of stellar fusion in the 1930s, elucidating the chains of nuclear reactions by which fusion built up heavier chemical elements and calculating the reaction rates and energy release. Astrophysicists were then incorporating plasmas into theories of stellar structure and thus merged the study of plasma with fusion.

Physicists at the time recognized the potential of fusion for a new energy source, but the high temperatures required to produce it seemed out of the reach of available technology. Although World War II and the coincident discovery of nuclear fission diverted attention from fusion, they would eventually provide the motivation and means to attain it. Nuclear fission and the subsequent development of nuclear bombs brought stellar conditions down to earth and offered a way to ignite fusion. During the war scientists working on the atomic bomb project in the United States discussed thermonuclear weapons, or the hydrogen bomb (named after its fuel), with explosive force orders of magnitude beyond fission bombs. Both the United States and the Soviet Union would pursue the hydrogen bomb in the Cold War; in the meantime, work on fission bombs advanced knowledge about plasma behavior, and the complicated hydrodynamic calculations for bomb physics spurred the development of electronic computers, which would then aid the development of fusion weapons.

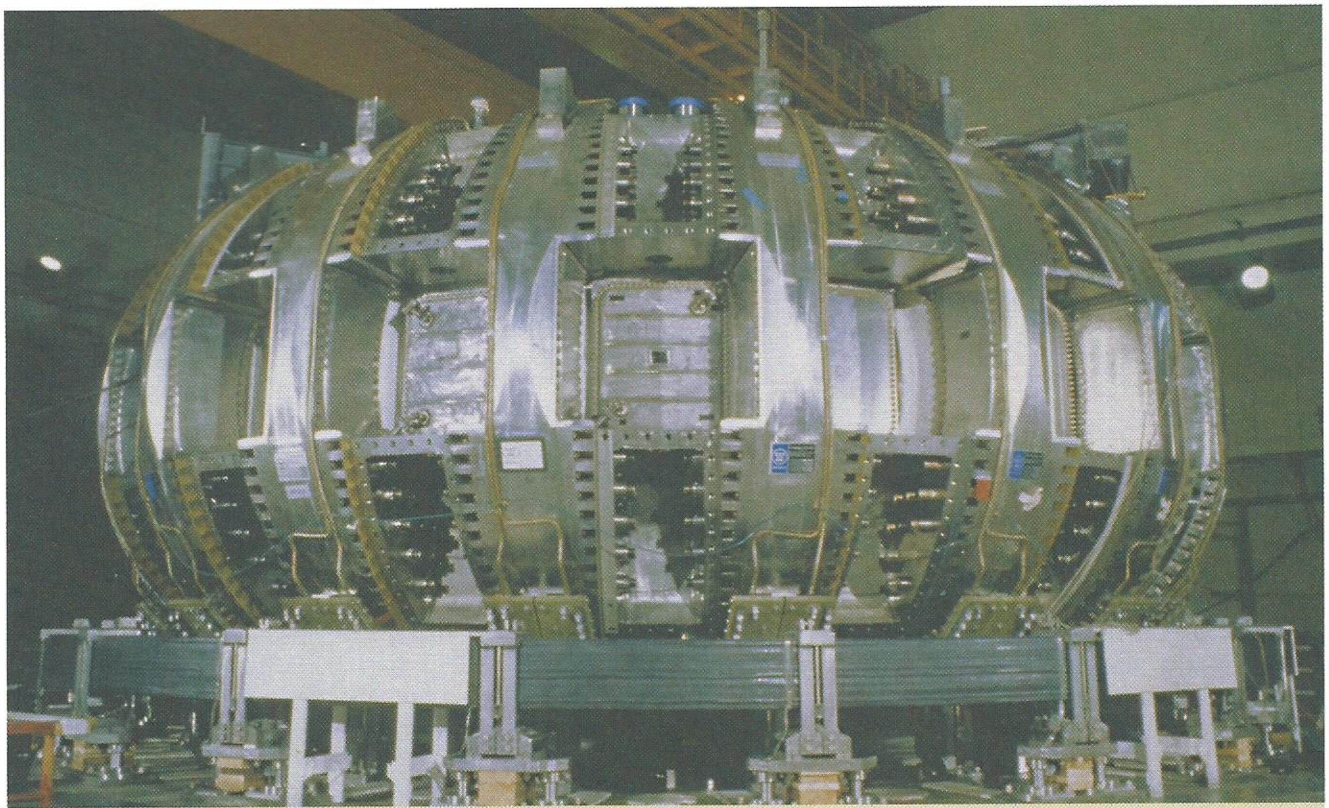
Research into controlled fusion revived in 1951 with the help of Juan Perón, the dictator of Argentina. A few years earlier Perón had set up a laboratory for Ronald Richter, an expatriate German with a scheme for controlled fusion power. In 1951, Perón announced Richter's successful production of power from a fusion reactor. The news made headlines in major newspapers, and though American and European scientists quickly discounted Richter's results, they did start thinking more seriously about the problem of fusion reactions.

One physicist so inspired was Lyman Spitzer, Jr., who was familiar with plasmas from his background in astrophysics and who had just joined a group at Princeton University working on the crash program to build the hydrogen bomb in the United States. Spitzer quickly devised a device to contain a plasma at high temperatures and obtained the support of the Atomic Energy Commission for the work. Commission laboratories at Los Alamos, New Mexico; Livermore, California; and Oak Ridge, Tennessee, soon followed suit. Controlled fusion seemed to offer unlimited power from an abundant fuel without the lingering radioactivity of nuclear fission reactors, and also provided a peaceful application of nuclear research to balance the fearful implications of nuclear weapons. It hence did not lack for support; by the late 1950s the United States was spending tens of millions of dollars a year on fusion research.

Other countries joined what became an international race for controlled fusion. British scientists led by George P. Thomson began investigating fusion soon after the war, and the British government sponsored a major fusion effort at its nuclear research laboratory at Harwell. In the Soviet Union, Igor Kurchatov, Igor Tamm, Andrei Sakharov, and other scientists in the nuclear weapons project took up fusion research in the early 1950s. The connection to nuclear weapons kept work in each country secret until Kurchatov revealed the Soviet program on a visit to Harwell in 1956; an international conference on atomic energy in Geneva in 1958 opened up the field for good. Japan, France, Italy, and other nations also entered the race, but the high cost of fusion experiments spurred efforts at international collaboration.

Most fusion reactors used various configurations of magnetic fields to bottle up the charged particles of the plasma, which at the high temperatures involved proved difficult to control. Fusion research engaged scientists from diverse fields: astrophysics, cosmic ray physics, accelerator engineering, gas discharges, and weapons physics. But no unified framework emerged from this eclectic background, and the initial optimism of the early 1950s soon gave way to realization of the technical difficulty of the endeavor—skeptics compared it to trying to push all the water to one side of your bathtub with your hands—and lack of knowledge about the basic behavior of plasmas. In the late 1950s, fusion researchers instead turned to the underlying theory of magnetohydrodynamics, although work on fusion reactors continued under more empirical techniques.

In the mid-1960s, Soviet scientists provided a new impetus with their development of the tokamak, which combined linear and toroidal configurations of previous devices in a single toroidal device. In 1968, a Soviet team under Lev Artsimovich revealed the attainment of temperatures of around ten million degrees and confinement times of about a millisecond in a tokamak. The tokamak thereafter became the preferred device for fusion, but the conditions it produced remained far below those required for fusion. Only after decades of technical refinements did a tokamak at Princeton University provide the first definitive success in late 1993 and 1994, when it confined a plasma of hydrogen isotopes at 300 million degrees Celsius for about a second to produce 10 million watts of power. The Princeton toka-



Princeton University's Tokamak Fusion Test reactor, a large device designed to retain a plasma at temperatures high enough to fuse helium nuclei

mak, however, still consumed more power in heating and confining the plasma than it produced.

The development of lasers in the 1960s suggested another route to fusion. Focusing high-energy lasers on a stationary solid pellet of hydrogen isotopes could compress and heat the pellet enough for fusion. Laser fusion—a form of inertial confinement—offered a way around the difficult problems posed by confining hot moving plasma with magnetic fields, and several nations started laser fusion programs. But laser fusion also presented daunting technical problems, especially the manufacture of laser optics capable of the high energies necessary. Connections with nuclear weapons persisted in laser fusion, since it also offered a way to model miniature nuclear explosions, and secrecy began to return to fusion research. In the 1990s, the United States began building the billion-dollar National Ignition Facility at Livermore to substitute laser fusion for full-scale nuclear tests.

Still another route to fusion energy was announced in Utah in March 1989 by B. Stanley Pons and Martin Fleischmann, who claimed to have obtained fusion at room temperature in a cheap and simple electrochemical experiment. The announcement set off a frenzy of popular discussion of limitless energy, but attempts to replicate the experiment and to adjust theory to accommodate the results failed. In addition, the disciplinary background of Pons and Fleischmann in chemistry did not inspire confidence in the physicists who dominated the fusion community, nor did their mode of announcement, in a press conference instead of through peer-reviewed publication. Cold fusion quickly joined N rays, polywater, and other famous nondiscoveries in the history of science.

PETER J. WESTWICK

PLATE TECTONICS. The theory of plate tectonics, proposed in the 1960s, asserts that the creation, motion, and destruction of a small number of rigid plates, thin in relation to the earth's diameter, shape the earth's surface. Quickly termed a revolution, the switch to plate tectonics was one of the most exciting scientific developments of the mid-twentieth century.

The discoveries that stimulated scientists to propose plate tectonics came from paleomagnetism and oceanography. At the end of the 1950s, a small but influential group of physicists based at the universities of London and Newcastle and at the Australian National University were studying paleomagnetism. They became convinced that to explain the apparent global wandering of the magnetic pole over geological time, they had to assume that the continents had moved relative to one another. They saw this as new evidence for the theory of continental drift, still widely discussed in Britain and Australia because it had been advocated in 1945 in the *Principles of Physical Geology* by the distinguished geologist Arthur Holmes.

Meanwhile, oceanographers had been surveying the ocean floor and measuring heat flow and gravitational and magnetic anomalies. They discovered a global system of mid-ocean ridges. These enormous mountain chains had some peculiar physical characteristics, such as patterns of magnetic anomalies and a median rift valley with high heat flow. In the early 1960s, Harry Hess of Princeton University suggested that these were tensional cracks through which lava welled up, created new sea floor, and spread. His conjecture of sea floor spreading was quickly corroborated by two confirmed predictions. In 1963, Fred Vine and Drummond Matthews of Cambridge University predicted that magnetic anomalies observed on either side of the mid-ocean ridges recorded global magnetic reversals preserved in the solidified lava. Physicists had dated global magnetic reversals on the continents using radioactivity and so had a magnetic time scale. It was only necessary to find parallel zebra stripes of anomalies on either side of the ocean ridges. In 1965, J. Tuzo Wilson predicted that if sea floor spreading occurred, scientists should be able to detect seismically a new kind of fault that he named "transform." In 1966, scientists at the Lamont Doherty Geological Observatory found evidence supporting both predictions.

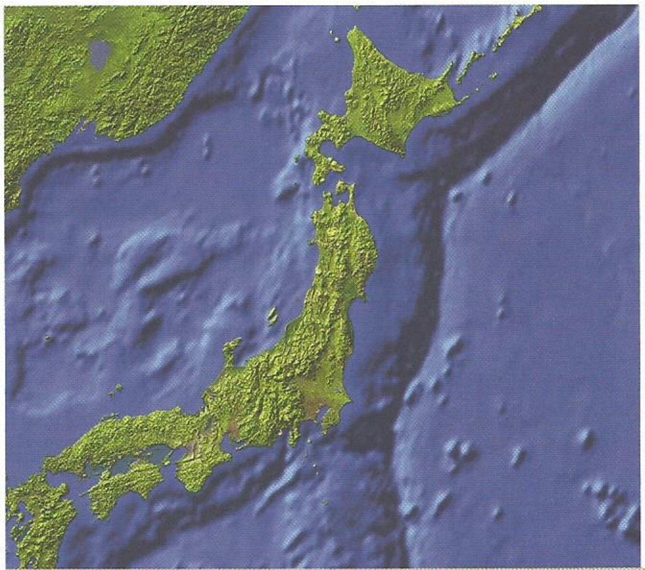
If the sea floor was spreading, where was the new material being accommodated? Could it be that the earth was expanding? Scientists gave this possibility serious consideration. It was quickly displaced, however, by the theory of plate tectonics independently conceived by Jason Morgan at Princeton and Dan McKenzie at Cambridge in 1967 and 1968, respectively. They proposed that rigid plates, each perhaps a hundred km thick, covered the earth's surface. They, and not continents and oceans, were the important structural surface features. Created at the mid-ocean ridges, they moved apart until they sank into and were consumed in "subduction zones" signaled by intense earthquake activity and negative gravity anomalies. Abstract mathematical models of plate movements agreed well with field observations. By the early 1970s, almost all earth scientists, except in Russia, had accepted plate tectonics.

Such a rapid shift to an account of the earth so radically different from previous orthodoxy stimulated popular interest. Earth scientists published in the popular scientific press, appeared on television programs, and revised school textbooks. Once their immediate euphoria waned, many earth scientists suffered a crisis of confidence. Were they wrong to have resisted the theory of continental drift for half a century? And if science proceeded by the patient accumulation of facts, as most of them believed, was it scientific to switch in just a few years from believing that the continents stayed in place to believing that they moved?

Many earth scientists, particularly younger ones, wondered how their predecessors could have rejected continental drift and derided it as pseudoscientific when it had been supported by some evidence from similarities of paleontology and lithology on the two sides of the Atlantic and from the fit of the continents. Their reaction misread history. Continental drift, like other theories put forward when the geological synthesis proposed by Eduard Suess in *Face of the Earth* (1883–1904) collapsed in the early years of the twentieth century, had been given a serious hearing. It was widely accepted in South Africa and viewed with an open mind by geologists in the British Isles and Australia. In the 1950s, some American geologists mocked it in their undergraduate classes largely because they believed its proponents lacked evidence. Plate tectonics, with its confirmed predictions, had much stronger evidential support; moreover, it was a different theory. The introduction of plates made continental movement an incidental theoretical consequence and not the key theoretical claim.

Earth scientists still had to face the fact that the speed with which they accepted plate tectonics did not sit well with their image of science as the gradual accumulation of facts. Casting around for an alternative picture of science, they came across Thomas Kuhn's *Structure of Scientific Revolutions* (1962). By the late 1960s, J. Tuzo Wilson and Allen Cox were describing plate tectonics as a Kuhnian revolution—an attribution still debated by historians and philosophers of science.

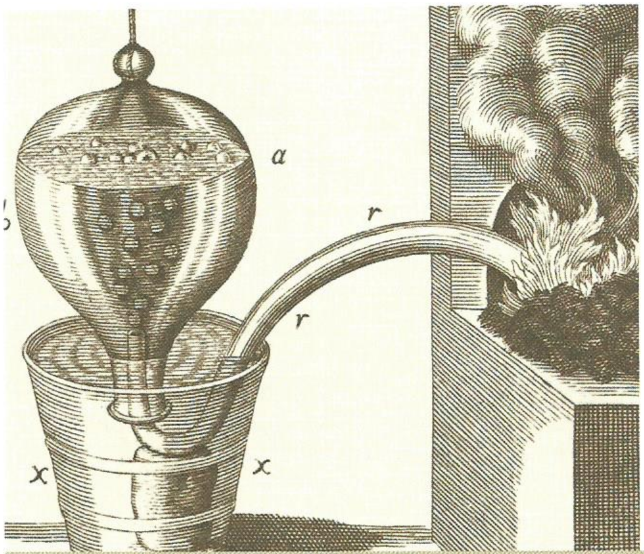
RACHEL LAUDAN



True-color satellite image of the islands of Japan. The Japan Trench (the dark line running from top right, forms part of the boundary of the Pacific and Eurasian tectonic plates. Plate movement and other tectonic features account for Japan's frequent earthquakes.

PNEUMATICS. The discovery of the different gas types during the third quarter of the eighteenth century caused a revolution in physical science. The new field of pneumatics made large demands on experimental technique and apparatus, and required unusual accuracy in calculating the weights of small quantities of matter. It played an important part in quantifying physical science and in forging fruitful connections among the branches of natural knowledge from anatomy (as in the work of Luigi Galvani) to chemistry (Joseph Priestley and Antoine-Laurent Lavoisier), meteorology (Jean André Deluc and John Dalton), and physics (Alessandro Volta).

The English clergyman Stephen Hales, who had learned Newtonian experimentation at Cambridge around 1700, pointed the way to pneumatics in his *Vegetable Staticks* of 1727. Hales described many ways of fixing "air" in, and liberating it from, vegetable and other matter. He collected liberated air over water in a "pneumatic trough" of his invention, measured its quantity, and studied its quality; but, although he handled several chemically distinct gases,



A pneumatic trough invented in the 18th century for the collection of various gas types he regarded them all as the same basic substance. The variety and quantity of substances from which he drew his "air," however, supported his conclusion, which he expressed in the Newtonian style as a query: "may we not with good reason adopt this now fixt, now volatile *Proteus* among the Chymical principles . . . notwithstanding it has hitherto been overlooked and rejected by Chymists, as no way entitled to the Denomination?"

Hales studied fixed air while following up his interest in the mechanics (physiology) of plants; Joseph Black came to the problem as a medical student concerned with kidney stones. For his doctoral thesis of 1754, he examined the air (carbon dioxide) released from magnesium alba (magnesium carbonate) when heated or treated with acid. He determined that it differed from common air in its inability to support combustion and respiration, and occurred fixed in the limestone implicated in urinary calculi. Novel airs then began to rise promiscuously. In 1766, Henry Cavendish identified a special "inflammable air" (hydrogen) as a product of metals dissolved in acids. In 1772, Priestley, teacher, divine, and experimental philosopher, inspired by reading Hales, announced the new species "nitrous air" (NO) and hydrochloric acid gas; and in 1774–1775 he introduced "eminently respirable air" (oxygen), the peculiar portion of ordinary air that maintains life. In 1776, his correspondent Volta discovered a second inflammable air (methane) while gas hunting in a swamp.

In the early 1780s, Cavendish, Lavoisier, and the inventor James Watt discovered that inflammable and eminently respirable air made water when sparked together. The rationale for the spark originated in Priestley's test for the respirability of gases: mix nitrous air with a sample under test and determine the contraction of the volume; the greater the diminution, the better the sample. (For oxygen the maximum contraction would be a third: $2NO + O_2 = 2NO_2$.) Volta had substituted inflammable gas for nitrous air and added the spark to speed up the process. He and other devotees of the new pneumatics devised "eudiometers" to test air by sparking. Thus they set up for themselves one of the grandest of all discoveries in physical science, the counterintuitive realization that gases that support combustion or burn freely combine to make the enemy of fire, water, and deprive it of its ancient right to be considered an element.

The discovery of the gas types led to a sweeping reformation of chemistry. It impelled natural philosophers to study the effects of heat on gases, which strengthened the caloric theory and supported measurements later important in thermodynamics. It had practical consequences before the end of the eighteenth century in the application of eudiometry to ventilation, in the craze of ballooning initiated by the Montgolfier brothers, and in the use of laughing gas (nitrous oxide) as an anesthetic.

J. L. HEILBRON

POLITICAL ECONOMY OF SCIENCE. During the past four centuries, the political economy of science—the nature and sources of its funding and the pertinent institutional arrangements—has changed primarily, though not exclusively, according to the political regime under which science has been pursued. In medieval Europe, the Church had created what Jacques Barzun once called the "House of Intellect"—those interested in scholarly subjects, including the phenomena of nature, pursued their interests in the universities of the time, usually as ordained clergy or as candidates for ordination. There were few divisions between the academic specialties that would later constitute "natural science." The sixteenth century, however, began to see major changes in the political economy of science, setting in motion complex adjustments between science and its environment that continue to the present.

Galileo's era marks the beginning of modern science not only because of the intellectual and technological advances of his time, but also because of an important shift in science's economic and institutional foundations. As a professor of mathematics at the University of Padua, Galileo belonged to the least admired stratum of academic life, and he multiplied the fault by deriving inspiration from the activities of artisans. When he left Padua in 1611 to join the Medici court in Florence, however, he insisted on the title of Philosopher and Mathematician, a coupling of the more prestigious contemplative work with the slighted practical pursuit. This combination of philosophy (physics) and mathematics became the high road of the Scientific Revolution. That Galileo felt he had to leave the university for a court to take his first steps on this road indicate the importance of private patronage in the political and intellectual economy of early modern science.

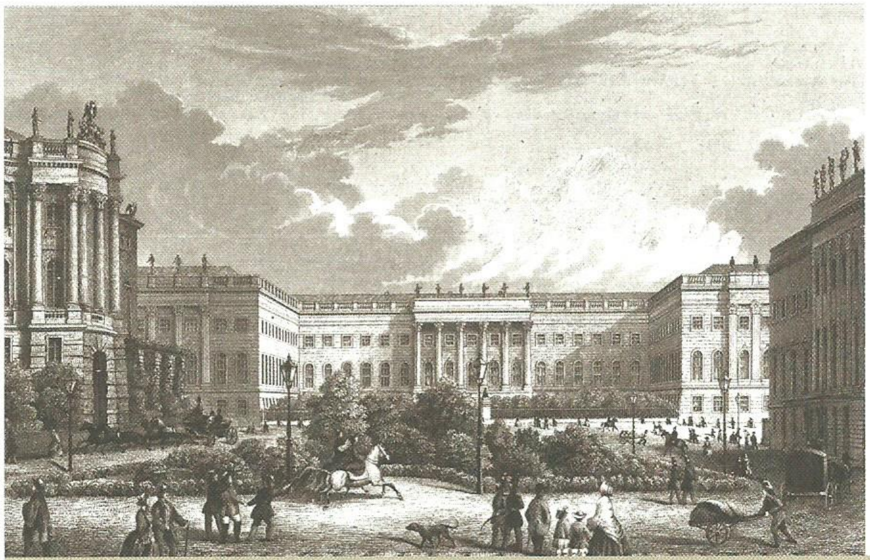
Galileo also enjoyed membership in another extra-university institutional form of first importance in the cultivation of natural knowledge from the mid-seventeenth to the mid-eighteenth centuries. This was the Academy dei Lincei, an academy without walls, a group of correspondents promoted and supported by a prince (Frederico Lesi) to pursue natural knowledge. Lesi's academy did not survive him. Nor did the more substantial group, the Academy del Cimento (1657–1667), composed of Galileo's disciples, outlast the interest of its patrons, the Medicis. But by the 1660s, the institution of the Academy, which brought people together to investigate nature and serve their patrons, had become the most important sites for natural science. The Royal Society of London and the Paris Académie Royale des Sciences date from that decade.

The Royal Society provided its own financing via dues and subscriptions and a large membership made up primarily of gentleman drones. The Paris Academy consisted of a small number of salaried experts who advised the state on technical matters and devoted most of their effort to astronomy, geology, cartography, and other mathematical sciences. The English model was imitated in Sweden, Holland, and the French provinces, the Parisian model in Berlin and St. Petersburg. The academic movement, which reached its height toward the end of the eighteenth century, provided institutional inspiration—though seldom the laboratory space—for the advancement rather than (as was the assignment of the universities) the spread of science.

The French Revolution inaugurated a new epoch in the political economy of science. The revolutionary government suppressed both the Académie and the universities in 1793. The Académie was to some degree reborn in 1795, as the First Class of the Institut de France, but for almost a decade, scientific and technical training took place exclusively in professional schools that survived the Revolution or in the newly founded grandes école. These institutions—especially the École Polytechnique and the École Normale Supérieur in Paris—had extraordinarily good faculties and adequate facilities. Their graduates enabled France to dominate European science. However, the new regime did not succeed in replacing the old universities and Jesuit colleges with suitable higher schools, especially in the provinces. The

University of Paris had "facultés" elsewhere, but these were generally poor, small, and ineffectual.

Many analysts considered the weakness of French higher education (apart from the grandes écoles) to be an important factor in the French defeat in the Franco-Prussian War (1870–1871). A number of initiatives—including financial contributions by local magnates and industrialists—sought to transcend these restraints. In 1896, after years of study, the national government reinstated the universities as comprehensive institutions and built important new science facilities at the Sorbonne. But the patterns of centralized administrative control, concentration of resources at the center, and the resulting flow of talent to Paris still hampered development.


The Humboldt University of Berlin, the first modern German research university, was built in 1810, in emulation and defiance of French scientific institutions.

Napoleon's invasions of Germany had aroused powerful nationalistic reactions that prompted sweeping reforms in German-speaking territories. Illustrated by the founding of the University of Berlin in 1810, these reforms, taken together laid the basis for the shift of the leadership of science to Germany. Paradoxically because of its long history of political disunity, Germany—newly united in 1871 after three wars with neighbors—had an important institutional advantage that helped it gain ascendancy in science. Each of its constituent states—Prussia, Bavaria, Saxony, and others—had its own universities; the newly unified Reich possessed twenty-two in all, and shortly after 1900, Frankfurt and Hamburg created their own municipal universities.

These schools, together with German-speaking universities elsewhere in Europe and the better Technische Hochshule, created a cooperative-competitive system that drove its faculties toward increasingly higher performance. Professors also moved between institutions based on their accomplishments, primarily publications and to some extent reputation, and they usually made a condition of their transfer (or of their staying put) the improvement of the facilities, an increase in their research provision, or the acquisition of more technical assistance. This internal elite migration spread innovation and expertise and enlarged the disciplines. A stream of important discoveries, inventions, and publications poured out of the German universities; an impressive number of students from European and other nations flowed into them.

German-speaking higher education retained the old tradition of representing whole fields of knowledge by a single full professor who supervised the work of subordinate junior faculty or graduate students in the same specialty. Under the system, new professorships could only be created at any given university by dividing an established discipline into smaller parts. Expansion could also occur by founding an entirely new university from the ground up. A strong and innovative professor could mobilize and concentrate resources; an indifferent and negligent one could ruin his discipline in his university for decades. And in any case, the low limit on the number of professors the system could absorb eventually sapped the morale of younger scientists. The problem was addressed—though never adequately solved—by various partnerships between government and private donors. In 1887, a large donation from Werner von Siemens had facilitated the creation of the state-run Physikalische-Technische Reichsanstalt. The years before World War I witnessed the founding of the Kaiser Wilhelm Society, which developed a wide network of specialized laboratories. Instigated by the chemist Emil Fischer, the humanist Adolf von Harnack, and several others, the Society attracted substantial private contributions from bankers, industrialists, and a few landed aristocrats. Their donations, together with funds allocated from the Prussian treasury, made possible the creation of an institution with historical importance for the political economy of science. But it too operated on the Führer-Prinzip: distinguished professors became institute directors with full authority—if they cared to exercise it—over their research staffs.

Invariably citing German developments in the political economy of science, the United States and Britain began to expand their educational and research facilities in the 1870s. Private capital in Sweden supported the creation of the Stockholm Högskola in 1878; dedicated almost exclusively to the natural sciences in its early years, the Högskola in 1960 became the state-run Stockholm University with a broader array of academic programs. Japan as a reformist state in the same period found both German and French models instructive. German precedents shaped the design of the so-called chair system in which a senior professor managed the budget together with the pedagogical and research activities of a subordinate younger staff. French examples influenced the national organization and important details of the internal structure. Following the Napoleonic model, Japan divided itself into regions, each of which was to have its own so-called imperial university. Each institution would have several chairs per discipline, dependent on enrollment and perceived academic needs. The one-chair rule, though widely debated, was explicitly rejected in Japan. A national system of elite universities, more equal to one another than the parent French institutions, gave rise to a competitive system favorable as such to the needs of modern science. The United States operated similarly, with multiple professorships, competitive appointments, and a unique use of government (state) and private monies. The Great War of 1914–1918 transformed the political economy of science. Geopolitical rivalries among several nations in the years leading up to the war had already stimulated greater political and financial support for science, and from a broader and more diverse stratum of society. Germany's rapidly paced industrialization between 1870 and 1914 had given it imposing strength in the realm of applied science—as in the large chemical companies and their corporate laboratories—to complement and support the strengths of science based in universities. The United States, and to some extent Britain and France, had also developed strength in company-based science; and although the German industrial research laboratories may have been more numerous and more generously funded, American corporations such as Westinghouse, AT&T, and DuPont were beginning to invest in long-term research. Germany's strength in applied chemistry enabled it to hold out against the Allied Powers until the spring of 1918. All of the leading military powers, including Japan, which entered the war on the Allied side, tried with mixed success to achieve equality with Germany in science, including its military applications.

Cut off by British blockade from its usual sources of raw materials, Germany soon ran short of strategic materials, notably nitrates for fertilizers and explosives. Fritz Haber, later director of the Kaiser Wilhelm Society's Institute for Physical Chemistry, had developed a means of producing ammonia synthetically in 1908. This achievement, when scaled up industrially, made Germany independent of imported nitrates. Haber also developed and oversaw the deployment of poison gas. The Allied nations faced the problem of finding substitutes for strategic materials previously obtained from Germany—optical glass, laboratory glassware, dyes, fine chemicals, and magnets. By the war's end, France, Britain, and the United States could make what they needed. Scientists on both sides helped to improve weapons, airplanes, radios, medical treatments, and so on. Agencies set up to mobilize scientific manpower and to provide it with resources—the Department of Scientific and Industrial Research in Britain, the National Research Council in the United States, and equivalents in the other belligerent countries—continued in many cases into the peace.

Imperial Russia was the first casualty of the war, not only because of inadequate military equipment, leadership, and training, but also because of its general backwardness in science. Following its defeat by Britain and France in the Crimean War (1854–1856), Russia had made efforts to catch its European rivals, founding several new universities, freeing the serfs, encouraging foreign investment, and promoting railway construction and industrialization. Significant weaknesses persisted, however. The underdeveloped state of Russian capitalism meant that private philanthropic support of science—increasingly important in Europe, the United States, and even Japan—had scarcely begun in Russia. With the Bolshevik Revolution in 1917, many Russians and their former allies believed that even the gains made in Czarist Russia would be lost. Nonetheless, the new regime preserved nineteenth-century advances and used them as a partial basis for subsequent development.

Several factors contributed to a smoother initial transition from one system of political economy in science to another than many observers expected. The new leadership dominated by V. I. Lenin, however autocratic by basic instinct, was flexible at first. Vigorous attempts by radical Bolsheviks to abolish the Academy of Sciences were defeated, with Lenin's concurrence. The regime desperately needed the services of the well-trained scientists and technical experts in rebuilding the country. Many professors, including leading figures like Ivan Pavlov, cooperated with the government. Moreover, the more prominent Bolshevik revolutionaries shared the Enlightenment vision of science. For them, science was not only the preeminent but also the only valid form of knowledge and the only reliable template for the reconstruction and maintenance of society.

Bolshevik radicals viewed the relatively tolerant policies of the 1920s as expedient at best, a betrayal of revolutionary egalitarianism at worst, and they were determined to dismantle the Academy of Sciences as a bastion of elitist reaction inherited from a discredited regime. Others charged the Academy with being obsessed with pure science, and insisted that all state agencies based on expert knowledge should have a strongly applied orientation. Many also favored a decentralization of research activities as a means of bringing technical knowledge closer to the clienteles that needed it. Stalin's consolidation of power created a favorable climate in which radicals might realize their vision of "science." They were only partly successful. Members of the Academy admitted a few party activists with minimally appropriate credentials, and opened its doors to engineers for the first time. Equally important in the Academy's survival was Stalin's own preference for centrally controlled institutions, even if they harbored individuals unsympathetic to his goals. The Academy of Sciences not only survived but became the institutional centerpiece and dominant agency in a new, highly centralized political economy of science. With minimal changes, this structure persisted almost to the end of the twentieth century.

Though the most extreme effects of the political economy of science were manifested in Russia, World War I had a large impact on the political economy of science in many countries. Scientists and their work in defeated Germany and Austria suffered intense privation in the first three years after the war, giving the hundreds of Japanese scientists who had earlier studied there the opportunity to repay their academic benefactors with gifts of cash, research equipment, and laboratory animals. Scientific establishments in the United States, Canada, and Britain acquired material resources on an unprecedented scale. Japanese scientists—accustomed to working under conditions of chronic privation—viewed the war as a "blessing from heaven." One consequence of the new largesse available to scientists in Japan was the founding of the Research Institute for Physics and Chemistry (1917–1922). A committee of three scientists proposed an Institute organized precisely in the manner of the Kaiser Wilhelm Society. With the active involvement of the wartime prime minister, Count Shigenobu Okuma, a finance committee raised large private gifts from the country's wealthiest citizens, the nobility, and the Imperial Family. Parliament matched these contributions, as in Germany, helping to create a more robust political economy of science than had existed in Japan previously.

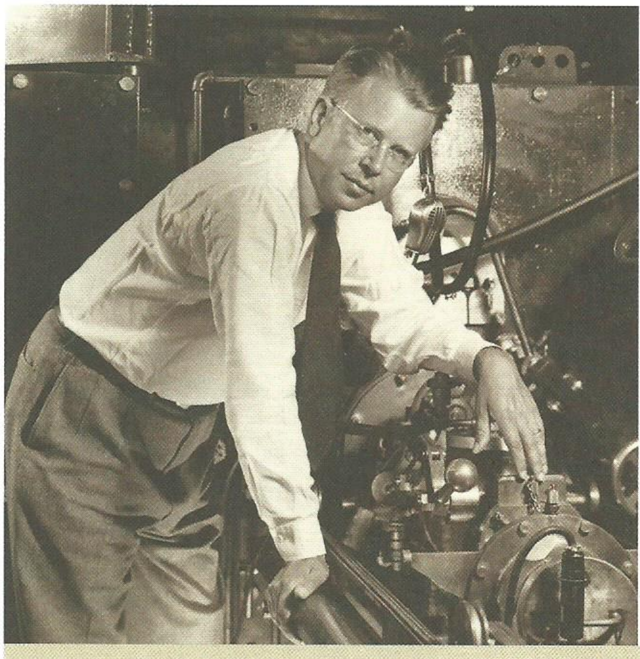
Yet another result of wartime experience had broad implications for science's political economy in many—probably most—of the nations active in research. This was the establishment of formalized systems by which investigators could submit research plans to review committees of peers and request a budget for particular projects. In many countries (Germany being an exception), pre-war university budgets had made no specific provision for research activity, even though research was becoming an essential part of the academic role. Scientists who worked in specialized laboratories—the Pasteur Institute in Paris, any of the Kaiser Wilhelm Institutes, the Carnegie Institute of Washington, the Solvay Institute (Belgium), and others—naturally had budgets dedicated to research. And in many countries, scientists could and did submit ad hoc requests to governments, private foundations, and other potential benefactors. In the wake of the war, governments began to create state agencies established specifically for the purpose of funding research without respect to the particular institutional affiliations of applicants. In some cases—Britain, the United States, and Japan among them—a newly created National Research Council performed this function; Japan created a special program for grant applications by scientists through its Ministry of Education. The Conseil National pour la Récherche Scientifique (CNRS) and Consiglio Nazionale delle Ricerche (CNR) had their beginnings in the interwar period. Germany created a number of special, self-help government and private agencies during the Weimar Republic.

By the 1930s, most features of the political economy of science that would appear in the twentieth century had cropped up in one country or another. Except in the Soviet Union, academies of science had come to function—when they existed at all—mostly as institutions for honoring scientific achievement after the fact, rather than supporting it materially in advance. The fundamental reason for the decline of the academies of Western Europe from the leadership of science in the eighteenth century to purveyors of honors in the twentieth was the professionalization of science in the nineteenth century and the establishment in most countries of the modern research university.

The Japan Society for the Promotion of Science (JSPS), founded in 1932, had as its primary purpose the allocation of financial support, after reviewing proposals, to large research projects considered important to national objectives but too costly for single universities to support. Itself a product of the surging militarism that followed Japan's seizure of Manchuria in 1931, the JSPS symbolized the trend toward ever-greater state influence in, and control over, science characteristic of the dictatorial states of the twentieth century. The trend began with World War I and continued with the Stalinist program in the Soviet Union and the Nazi regime in Germany. But apart from certain police interventions, the Nazis used ideological rather than institutional tools to achieve their purpose. The pre-Nazi political economy of science in a formalist sense remained intact even as Jewish academics were ejected or imprisoned. Partly because of the Soviet Union's seemingly rapid development in the 1930s, and partly also owing to their fears of Nazism and Fascism, some scientists—especially in Britain, France, and the United States—began to promote Soviet notions of the political economy of science, or at least to debate the relative merits of democratic and socialistic support systems. Much of what transpired during World War II with respect to the political economy of science repeated the experience of the Great War on an even larger scale. The United States as well as Germany, Japan, and the Soviet Union sought to capitalize on the late 1930s discovery of fission by developing an atomic bomb for wartime use. But these projects are only the best-known examples of institutional changes in science's political economy. The earlier development of the cyclotron by E. O. Lawrence after 1929 set in motion a process of institutional growth in high-energy physics that continued almost to the present. A similar trend later appeared in other research specialties, and continues to the present, where it most recently has arrived in the biological sciences. The early decades of the Cold War saw a continuation of wartime patterns. Rivalry in almost every sphere of human activity led the United States and the Soviet Union to inexorably greater expenditures on science and technology, exemplified by the *Sputnik* program of artificial satellite development and the successive *Apollo* missions of lunar exploration. The Soviet satellites followed the Soviet lead as best they could. Western Europe did the same with the United States as its model, and after Americanizing, have caught up in some respects. The innovative, cooperative research enterprise of CERN, for example, brought western Europe to parity with the United States in accelerator and particle physics, and it will soon be ahead.

Partly because of Soviet wartime successes and the evident promise of rapid economic and technological development, many developing nations after World War II tried to copy the Soviet model of the political economy of science. Building on a small-scale model developed in the 1930s before the Japanese invasion of 1937, the People's Republic of China under Mao Zedong imported hundreds of Soviet technicians and science advisers. With their help, China in the 1950s created a near-perfect replica of the Stalinist system, based on the central role of the Chinese Academy of Sciences. Attracting émigré scientists from the United States and elsewhere, the PRC managed to develop its own atomic bomb in 1964 and even more advanced weapons in later years. While the Chinese initiatives may seem extreme, the general model of state-led development in science they embodied was more broadly characteristic of the period as a whole.

It appears that the state-led pattern of growth in the political economy of science is sharply decelerating. Countries that once had no private universities, such as Australia and Britain, now have one or more; in others, such as the United States, the ranking private universities are better funded than ever, while the leading public institutions sometimes have to struggle to stay even. Japan, long a bastion of French-style étatism in higher education, has announced a plan to privatize virtually all so-called national and other public universities over the next decade or so. Russia, in the aftermath of the Soviet Union's dissolution, has begun to restore a role for the private sector in science that had disappeared in the Revolution. The government of the United States, at the insistence of Congress, in 1993 terminated the costly Super-Conducting Super Collider in Texas. And in a public-private competition between researchers investigating the human



Ernest Orlando Lawrence (1901–1958), inventor of the cyclotron and impresario of Big Science genome, a private firm won a tentative victory over a government-funded team. How far these trends will proceed or when they might reverse cannot be anticipated. The future of the political economy of science is as difficult to predict as the future of nation-states themselves. But the two have developed in tandem, and each is a work in progress.

JAMES BARTHOLOMEW

POPULATION GENETICS is the science concerned with the inheritance and distribution of gene frequencies in a given population. Evolutionary population genetics, from which this branch of study arose, deals with changes in these distribution and inheritance patterns over time. The roots of the discipline originated in the period following the publication of Charles Darwin's *On the Origin of Species* in 1859, when a debate raged within biology about the kind of traits upon which natural selection works. Were they small physical changes in an organism, as Darwin, August Weismann, and Alfred Russel Wallace thought, eliciting a slow, gradual evolution? Or did nature proceed by jumps, fashioning new species in rapid discontinuous leaps, as Thomas Henry Huxley and Francis Gallon believed? Galton, Darwin's first cousin, argued that selection of continuous traits would be rendered ineffective by the law of regression—a mathematical formulation of the tendency of offspring characters to regress to the mean of the population. The further down an ancestral path from a new trait, such as a bent nose, the likelier it became that the nose would straighten out. If so, natural selection acting on small, continuous changes could not be responsible for evolution. Galton concluded that only by acting upon discontinuous novelties, such as a completely new nose form, could selection bring about evolution.

With the rediscovery of Gregor Mendel's laws in 1900, the old debate quickly found new proponents. The experiments of Hugo de Vries on the evening primrose in his Amsterdam garden gave rise in 1903 to the theory that spontaneous, internal, and discontinuous mutations in the hereditary substance were genetic mechanisms capable of explaining evolution. Mendelians, led in England by William Bateson, came to believe that Darwin, who thought of natural selection as a creative force, had it wrong on both counts: Evolution was neither gradual, nor brought about by selection. It was disruptive, motored by discontinuous, internal changes to the hereditary material unaffected by the environment. The most nature could do was to eliminate those deleterious varieties presented before her and propagate the rest.

A Biometric School, led by Karl Pearson and Walter Frank Raphael Weldon in England, rejected the Mendelian recourse to a heredity based on unseen, theoretical, genetic "factors." They defined inheritance instead in terms of Galton's law of regression, based on the wide range of measurable, perceivable, and continuous physical variations. Pearson argued that Galton had misinterpreted his own law: if the relation between traits of offspring to the mean of their parents, rather than that of the population, were considered, swamping (the gradual erasure of a new trait) would disappear, and Darwin's picture of gradual, continuous evolution by natural selection would be upheld. Fierce debates raged between the biometricians and the Mendelians in England. Mendelian particulate heredity and Darwinian gradual evolution by natural selection appeared to be diametrically opposed.

Darwin's proposed mechanism of natural selection was by now coming under severe attack. In 1902, the Swedish biologist Wilhelm Johannsen had shown that natural selection acting on continuous variation could not overcome Galton's law of regression: it failed to induce evolution within pure lines. Experimental Mendelians took this as strong evidence against Darwinian gradualism. They refused to admit a role for adaptation and selection in the control of those novel variations produced by mutation in their laboratories. At the opposite extreme, field naturalists, who saw variation manifested abundantly, rejected mutationism and endorsed the principle of gradualism, but advocated Lamarckian mechanisms of heredity to buttress, or replace, what they took to be inadequate selection. Embryologists and paleontologists added to the chorus of discontent with natural selection, advocating Lamarckism and other forms of orthogenetic, or directed inheritance, to explain the adaptations they recognized. The divided biological landscape made imperative the need to establish both the kind of variations upon which selection worked, and the extent to which such a force could be shown to be responsible for evolution.

The first problem was gradually settled in the first two decades of the twentieth century through the work of W. E. Castle, Edward Murray East, H. Nilsson-Ehle, and the so-called Fly Room group of Thomas Hunt Morgan. Their experimental results showed how continuous hereditary variation could be explained by discontinuous variation produced by small genetic mutations. The Biometric-Mendelian debate had been settled, but entrenched conceptions proved hard to dispel. In 1908, an English mathematician, G. H. Hardy, and a German physician, Wilhelm Weinberg, independently derived a simple yet crucial quantitative rule, expressing the idea that gene frequencies, or proportions, would remain constant unless acted upon by external forces. The Hardy-Weinberg equilibrium, $P^2 + 2PQ + Q^2 = 1$, where P is the frequency of a dominant allele *A*, and Q the frequency of a recessive allele *a*, had some very useful properties. (Alleles are alternative genes at the same locus.) In a population with a gene locus with a dominant allele *A* and a recessive allele *a*, only two phenotypes are visible: homozygous recessives *aa*, and a class exhibiting the dominant trait comprising a mix of *AA* and *Aa* individuals. The Hardy-Weinberg rule allowed calculation of the proportion of heterozygotes, or carriers, of recessive alleles for human genetic disease in the population, and thus a better understanding of the propagation of disease. Notwithstanding the importance of this basic and useful rule, it remained to be shown whether selection, acting on discontinuous genes and in conjunction with other variables, would explain evolution. R. A. Fisher and J. B. S. Haldane in England, and Sewall Wright in the United States, tackled this problem and founded theoretical population genetics.

Adopting a biometric, mathematical population approach, the three men defined evolution as the differential inheritance and propagation of gene frequencies over time. By assigning adaptive values with respect to fitness to different gene alleles, it became possible to calculate how selection could fashion their respective frequencies in the population. Fisher worked primarily on models with low selection pressures on individual genes in large populations; Haldane on high selection pressures on individual genes in large populations; and Wright on intermediate selection pressures on interactive gene systems in small, partially isolated, interbreeding populations. Although their models emphasized different aspects of evolution and led to disagreements, they all used the gene, not the individual organism, as the functional unit of selection. Together with the quantifiable factors of mutation and migration rate, effective population size, and mating behavior, selection was shown to suffice as a mechanism for evolution. The force it exercised was powerful enough to render Lamarckian and other forms of directed change superfluous. Haldane, for example, estimated the mutation rate of a deleterious gene in a human population, that for hemophilia, and suggested that differential susceptibility to disease might have driven much of human evolution.

Theoretical population genetics, developed in the 1920s and generally adopted after 1932, dispelled the legacy of anti-Darwinian feeling by synthesizing genetic gradualism with Darwin's theory of natural selection. But while providing a correct picture of genetic change in a given local population, what has been called the "bean-bag" genetics of these pioneers failed to explain adequately the interaction between genes and gene systems, macro-evolutionary changes such as adaptation, the origin of higher taxa and novel evolutionary forms, and the multiplication of species. In order to satisfy the organismic phenomena studied by ecologists, systematists, paleontologists, and students of behavior, and to complete what became known as the Evolutionary Synthesis, a further step of translation and modification of the mathematical models to the more complex realities of natural populations was necessary. The work of the Russian school of experimental population genetics led by Sergei Chetverikov, the interpretation of Fisher's work by the ecologist E. B. Ford and of Wright's work by the geneticist Theodosius Dobzhansky, the labors of the systematist Ernst Mayr, and the popularizations of Huxley's grandson Julian all figured significantly in this endeavor. The synthesis was generally achieved by mid-century.

Population genetics has had important implications for a range of fields from eugenics to breeding, ecology, and demography. With the development of techniques in molecular genetics, human population genetics has been employed in studies traditionally dominated by anthropology, archaeology, and linguistics to help researchers understand the history of global and local migration patterns, language evolution, and cultural and technological diffusion. Medical research has increasingly employed methods from population genetics in the study of disease.

Oren Solomon Harman

PRIMATOLOGY. Europeans who penetrated the jungles of Asia and Africa during the eighteenth century brought back tales of half-human monsters. Skeptics demanded proof, and the obliging adventurers returned to the jungles to kidnap infant chimpanzees, gorillas, and orangutans. These small animals arrived in Europe orphans—their mothers had been killed to capture them—and sick from weeks at sea and a poor diet. They seldom survived more than a year, leaving their skulls and skins for examination.

Carl Linnaeus used these relics to classify the primates, today divided into four lineages: apes, Old World monkeys, New World monkeys, and prosimians. Linnaeus lumped the tailless great apes with humans in the family *Hominoidea*. Primatology has focused on *Hominoidea,* where Linnaeus's taxonomy, though fine-tuned during the last two centuries, has persisted with surprisingly few major changes. Today some taxonomers add a fourth species to his three great apes—chimpanzees (*Pan troglodytes*), gorillas (*Gorilla gorilla*), and orangutans (*Pongo pygmaeus*); the fourth candidate, bonobo, is sometimes classified as *Pan paniscus,* a distinct species of chimpanzee, or as *Bonobo paniscus,* a separate genus. Linnaeus's arrangement of the hominids has also expanded to include the discoveries of hominid fossils, which have added extinct species to both ape and human family trees. Radiocarbon dating has shown that our ancestors diverged from the ape ancestors around thirty million years ago. DNA studies have shown the apes to be more closely related to humans than to any other primates. The chimpanzee stands genetically closest of all to *Homo sapiens.*

Charles Darwin would not have been surprised. In *The Origin of Species* (1859) he suggested that human beings share a common ancestor with other primates. Later, in *The Descent of Man* (1871), he characterized the haunting familiarity between humans and apes as a family resemblance. We

Jane Goodall (b. 1934), British conservationist and zoologist share, he demonstrated, emotions and expressions as well as a similar skull and skeleton.

At the end of the nineteenth century students of the new science of psychology began exploring the abilities of the great apes in comparison to each other and to human beings. With the exception of Richard L. Garner, an American zoologist who went to West Africa in the 1890s where he sat in a cage while observing wild chimpanzees, the early primatologists studied only captive apes. In 1927, the German psychologist Wolfgang Köhler described his colony of chimpanzees on the island of Tenerife, near Spain, who stacked boxes to retrieve bananas. At about the same time in the United States, Robert Mearns Yerkes studied a pair of chimpanzees at his summer home in New Hampshire and traveled to meet and test gorillas and orangutans wherever he could find them. Eventually he established breeding colonies of apes in Orange Park, Florida. He compared the three great apes anatomically, physiologically, and behaviorally and published his results in 1929 in a massive volume, *The Great Apes: A Study of Anthropoid Life,* coauthored with his wife, Ada. Yerkes was remarkably prescient about ape intelligence and, contrary to the habits of his colleagues, he gave his experimental animals names, rather than numbers, because he found that their personalities were so distinctive as to make numbers inappropriate. Yerkes acquired his first chimp in 1923 and named him Bill, after William Jennings Bryan, the prosecutor in the Scopes Trial.

As much as he enjoyed keeping them in his laboratory, Yerkes realized the importance of observing apes in their natural habitats and found enough money in the depths of the depression in 1930 to send his student Henry Nissen to West Africa for four months. But the continued economic woes of the 1930s, followed by World War II and revolutions and civil wars in Africa and Asia, prevented the development of field studies until the 1960s. Then, at almost the same time, Dutch, Japanese, British, and American primatologists went individually and in groups to observe wild apes in Africa, Sumatra, and Borneo.

These observers habituated the wild animals to their presence and established field stations to plot the behavior of individual animals as well as groups. With support from the National Geographic Society Jane Goodall, Dian Fossey, and Birute Galdikas set up projects in Tanzania, Rwanda, and Borneo. At the same time, Junichero Itani and his Japanese colleagues began studies of chimpanzees and bonobo in central Africa. Most of these projects continued for several decades. They revealed that each ape had an individual personality that determined the nature of each family group, and that each group of apes had a separate culture. Some used tools; some hunted for meat. The primatologists who conducted these studies in the early years of the women's movement consisted of women and men in equal number. Whether gender bias had skewed earlier research is hard to assess, but research in the last decades of the twentieth century showed the powerful role of females in ape societies.

Meanwhile increasing evidence of the genetic nature of apes made them the ideal stand-in for humans in studies ranging from the evolution of the brain to medical models for HIV-AIDS. NASA's confidence in chimp intelligence led to chimpanzee "pilots" in spacecraft of the early 1960s. At the same time psychologists and linguists in the United States began experiments to test whether apes could communicate with American Sign Language and with symbols. Though their degree of grammatical mastery of language is controversial, some chimpanzees have passed on the skills they learned to two generations of offspring.

The species most similar in behavior to humans is the bonobo, who live in a single area in the Congo. They enjoy a very complicated social life that includes frequent sexual activity, homosexual as well as heterosexual. These exchanges apparently serve as displacement behavior to avert aggression within the group.

Great apes behave differently in the wild and in captivity. Chimpanzees use tools in the wild. Gorillas do not, but in captivity perform very well on tests demanding small muscle coordination. Orangutans occasionally use tools in the wild and are especially clever at escaping from zoo confinement. All reveal a sense of humor in the way they play tricks on each other and on their human guardians.

The population of wild apes dwindled drastically in the last decade of the twentieth century as their habitats became the sites of human wars and ecological exploitation. Wild apes probably will not survive for long without dramatic policy changes. Apes in zoos and wild animal parks may live a life similar to one in the wild. Others may continue to suffer as medical models for human disease.

Philosophers and lawyers now dispute the nature of ape awareness and self-consciousness, and their entitlement to greater protection. Activists, led by Jane Goodall, are trying to have laws interpreted so as to give apes legal protection against experimentation and exploitation. Without increased protection, our fellow *Hominoidea* will soon be extinct, and their branch of primatology will become a historic science like paleontology.

BETTYANN HOLTZMANN KEVLES

PROBABILITY AND CHANCE. Civilization has always known games of chance. Throughout history, societies have guessed their future by reading entrails, tea leaves, or the accidental arrangement of other objects, and have made crucial legal decisions by lot. Christians deemed gambling a vice, but new games of chance entered Europe from the Arab world during the Crusades. In the mid-thirteenth century, about the time clocks were introduced into the town square, a poem called "De vetula" conceived of dice throwing in terms of frequencies. Cards appeared in the fourteenth century, complicating games of chance. Girolamo Cardano's *De ludo aleae* (1663) defined chance events in terms of their frequency of occurrence. During the Scientific Revolution, when the nature of evidence and causes was debated, Blaise Pascal and Pierre de Fermat corresponded about chance, Christiaan Huygens wrote a book on it, and Jakob Bernoulli I, in his *Ars conjectandi* (1713), presented the binomial distribution and considered how random events might create a regularity with more than a grain of truth.

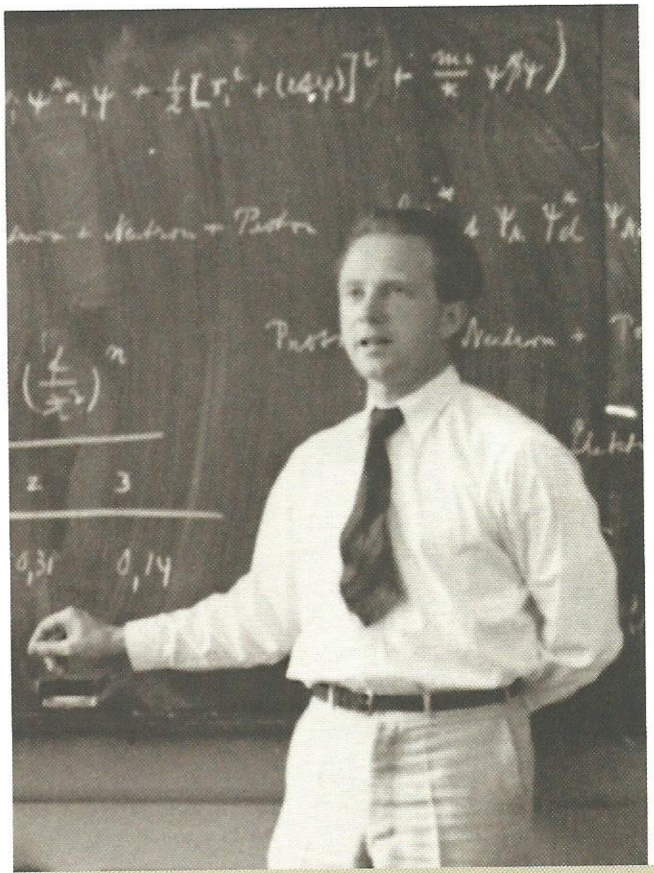
Classical probability can be regarded as both empirical (chance as the frequency of events) and epistemic (probability as the mental state of doubt related to degrees of belief, a notion that goes back to medieval times). Probability was thus a state of opinion, perhaps related to authority and testimony, but not as demonstratively true knowledge. The empirical and the epistemic issues in probability shaped discussions on the nature and acceptability of evidence, proof, belief, and truth in early modern Europe. But the subjective and objective sides of probability could not be so cleanly separated in practice. When David Hume showed in 1737 how probability could be used to validate inductive evidence, opinion and knowledge became only differences of degree, not kind. The age of classical probability, which lasted until the mid-nineteenth century, had opened.

The shift to a mathematical theory of probability started with Pierre-Simon de Laplace's *Analytical Theory of Probabilities* (1812). Chance had begun to look lawful in the eighteenth-century analysis of errors, but now with Laplace's definition of the probability of an event as the ratio of the number of favorable cases to all possible cases, probability theory could be applied to a wide variety of events in the social and physical worlds. Yet probability continued also to refer to incomplete knowledge about matters both esoteric and everyday, about matters that possessed only partial or moral certainty, not absolute certainty. The objective and subjective sides of probability thus collapsed on one another during its classical phase; objective frequencies of events were also subjective degrees of belief. Probability had to do with uncovering the lawful in randomness, and with degrees of ignorance and doubt.

Around the mid-nineteenth century, consideration of large-scale regularities—gambling problems, actuarial computations, demographic patterns, errors as treated in the method of least squares, and the like—shifted the emphasis in probability theory more toward the frequency or ratio of events in the world and less toward assessments of epistemic certainty. Especially in what was then known as "social physics," probability appeared to be more about objectivity than subjectivity. Lambert-Adolphe-Jacques Quetelet, the founder of modern statistical methods, announced in 1844 that the error law used in astronomy could be applied to the distribution of human features, such as height: human variation thus could be understood in the same terms as errors of observation. Quetelet used the bell curve of error analysis to propose the "average man," a new object of investigation that occupied the same position on the error curve as the most probable measurement. The most likely value with the smallest error was an experimental ideal; the average man, a moral one. Mass phenomena or repeatable events became the focus of Wilhelm Lexis's sociology in his *Theory of Mass Phenomena in Human Society* (1877), and the foundation of Richard von Mises's probability calculus in 1919.

In no field was the shift to an objective probability more apparent than physics. The deterministic ideal of classical physics allowed only for an epistemic interpretation of probability (which had been the interpretation of Jakob Bernoulli and Laplace), as was the custom in error theory. Moreover, objects of investigation in physics seemed so well defined that recourse to a composite construction, analogous to Quetelet's average man, was unnecessary. But then the British physicist James Clerk Maxwell announced in 1860 that the velocities of gas molecules had a bell curve distribution, like errors. Classical physics, which was deterministic and postulated continuous (if not reversible) behavior, appeared unable to describe the intimate behavior of a system of gas molecules. Ludwig Boltzmann found that in order to understand the second law of thermodynamics—announced by Rudolf Clausius in 1850 as the irreversible increase in entropy over time—he had to use probability theory applied to molecular behavior. In Boltzmann's interpretation, entropy became a macroscopic measure of the probability of finding a system in a particular state, the most probable state being one of maximum entropy. Finally, discontinuities in matter and energy could only be understood in statistical terms. Using probability theory, Albert Einstein confirmed the existence of discrete atoms in his study of Brownian motion (1905). Discontinuous energy processes—black body radiation, radioactive decay, the photoelectric effect, and atomic and molecular spectra—could also only be understood through probability theory. In his study of black body radiation, Max Planck introduced what became known as energy quanta via a statistical theory of heat (1900). In quantum mechanics, in both Werner Heisenberg's matrix mechanics and Erwin Schrödinger's wave mechanics, the likelihood of measuring a system in a given state became a probability of how likely the state was to occur. Heisenberg's famous uncertainty principle incorporates the notion that at the subatomic level properties could not be measured precisely, but only given a probability distribution. Despite his reliance on the word "uncertainty," Heisenberg did not refer to degree of belief, but to the irreducibly statistical character of subatomic reality.

Kathryn Olesko



Werner Heisenberg (1901–1976), who introduced the principle of uncertainty into quantum physics, lecturing in 1936

PROFESSIONAL SOCIETY. Societies designed to affirm and serve the professional interests of members of disciplines or other scientific groupings came into existence in the late nineteenth century. The fields that first provided professional scientific employment on a large scale were those like chemistry that found a significant role not only in the burgeoning educational system but also in industrial, commercial, and state organizations in the major economies of the world. The sharing and advancement of scientific knowledge had been the chief rationale of academies and learned societies since the seventeenth century, but professional societies had a wider occupational relationship to scientific knowledge, its possessors, and its diffusion.

Early professional societies, such as the Institute of Chemistry in the United Kingdom (founded in 1877), were designed primarily as qualifying associations. The Institute membership initially overlapped considerably with the dis-

Elizabeth Brown (1830–1899), self-taught English solar astronomer, was instrumental in setting up the British Astronomical Association, which, unlike the Royal Astronomical Society, accepted women as members.

ciplinary Chemical Society of London, but had different objectives: to promote the thorough study of chemistry and related sciences in their application to the arts, manufacture, agriculture, and public health (and thereby promote professional standards); to ensure the competence via certified training of consulting or analytical chemists; and to maintain the profession on a satisfactory basis. Acquiring a Royal Charter in 1885, the Institute gained the right to grant certificates of competence. However, the strong academic membership and the practical and ideological difficulties of representing the membership in salary questions limited its role. The Institute strenuously avoided any suggestion of trade unionism. The British Institute of Physics was established in 1921, when the expansion and diversification of physicists' employment had generated enough concern for coherent representation and promotion of their collective fortunes. The Institute of Biology (1950) met the felt need to give an authoritative voice to British biology as a whole.

The United States followed the same sequence of foundations, though telescoped in time because of the later maturity, but greater volume and more rapid growth, of scientific employment there. Thus the establishment of the American Institute of Chemistry (1923), the American Institute of Physics (1931), and the American Institute of Biological Societies (1947). The membership of the American Physical Society (1899) had been ambivalent about representing the employment and other interests of physicists. Most members gladly ceded this role to the American Institute of Physics (AIP). Apart from catering to the occupational and professional interests of their members, the institutes also sought to secure a sense of common identity among scientists from ever more specialized fields. The AIP consisted of the Physical Society, Optical Society, Acoustical Society, the Society of Rheology, and the American Association of Physics Teachers. More societies joined after the mid-1960s. By the 1990s, the AIP, with a staff of 500, represented over 100,000 physicists. The striving for a common identity among the biological disciplines in the United States resulted first in the American Society of Naturalists and then the American Society of Zoologists. World War II brought home the need for an integrated society in the biological sciences to make the government and the public aware of the coherent body of manpower it represented.

In Continental Europe, patterns of development differed. The Deutsche Physikalische Gesellschaft (DPG) traces its origins to the Physikalische Gesellschaft of Berlin formed in 1845. The DPG, with its range of national and professional functions, did not emerge from these local beginnings until 1899. After World War II, the DPG reformed without the Eastern bloc members and began publication of a general news magazine, *Physikalische Blätter*. By contrast, the Société Française de Physique, formed in 1873, was nationally recognized by decree in 1881 and then grew to coordinate an elaborate structure of local sections, specialist divisions, and publications, including the *Journal de Physique* and *Annales de Physique*.

Professional societies typically have several levels of membership: student (or associate), full, and fellow. Honorary fellows, presidents, and patrons selected from the disciplinary elite symbolized the bridge between the professional institutes and the more traditional learned societies. Sometimes, new institutes stimulated older societies to take on new roles. The American Institute of Chemistry was founded in part because of dissatisfaction with the professional consciousness of the American Chemical Society, which greatly expanded its role in professional affairs beginning in the 1930s. As a result, the society remained the dominant institution for rank-and-file chemists. The American Psychological Association (APA) began as a disciplinary society, saw the foundation of more professionally oriented bodies (notably the American Association for Applied Psychology, founded in 1937), and re-formed after World War II along the institute model.

Publication of research journals, abstracts, and periodicals concerned with the educational, applied, and popular aspects of their field has been a major concern of professional societies. The AIP was formed in part to publish the journals of its member societies in uniform format through a common editorial office. It subsequently acquired or established other journals, including *Physics Today,* like *Physikalische Blätter* a vehicle of news and articles of general interest to physicists. The APA bought up several psychology journals. However, its stable of journals, even as it expanded, represented a decreasing relative proportion of the psychology journals published. Compared with the United States, European and other professional societies have been less active in publication and more reliant on private-sector science publishers.

British and American institutional models have been widely adopted elsewhere in the English-speaking world. Examples include the Royal Australian Chemical Institute, the New Zealand Institute of Physics, and the Canadian Association of Physicists. Cognate institutions exist in most developed societies. More recent foundations for physicists include Nippon Butsuri Gakkai (1946), the Israel Physical Society (1954), the South African Institute of Physics (1955), and the Dansk Fysisk Selskab (1972). The international European Physical Society (founded in 1968) represents over 80,000 physicists through 36 national member societies, for whom it acts as a federation and presents a European perspective in international forums.

The effort continues to coordinate, integrate, and effectively represent to the wider world the knowledge production and professional interests of scientific researchers and workers in the face of ever more specialization and occupational diversity.

David Philip Miller

PULSARS AND QUASARS. Exotic astronomical objects were first detected in the 1960s by their radio emissions, though most quasars (quasi-stellar radio sources) are radio quiet. Pulsars are pulsating radio sources.

In 1960, astronomers identified the radio source 3C48 (number 48 in the Third Cambridge Catalogue) with a star-like object. Three years later, they did the same for 3C273, which had emission lines at unusual wavelengths. Maarten Schmidt at the Mount Palomar Observatory in Southern California recognized the mysterious spectral lines as lines from common elements shifted far toward the red. One mystery solved led to another. Assuming the red shifts arose from the expansion of the universe, astronomers had to endow quasars with tremendous speeds and distances. To be visible at vast distances, a quasar would have to be enormously bright, a thousand times brighter than all the stars in our galaxy. But a quasar's rapid variation in time would require that its energy be produced in a small volume. No known nuclear process can yield the observed energy output from a small volume.

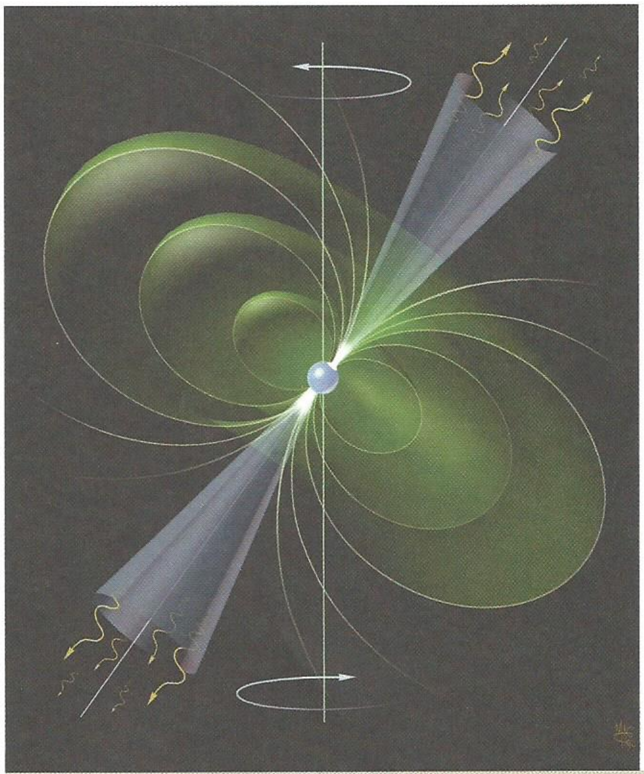
The need for new physical explanations for new astronomical phenomena expanded further. In 1967, Anthony Hewish and Jocelyn Bell at Cambridge University, looking for rapid variations in the radio brightness of quasars, discovered a rapidly pulsating radio source. The radiation had to be from a source not larger than a planet if the signal could spread so quickly across the object to trigger bursts of radiation. Hewish won a Nobel Prize for the discovery, though his student Bell made the actual observation.

The period of this pulsar, 1.3 seconds, was so regular that Hewish and Bell briefly thought it might be an interstellar beacon or radio lighthouse built by an alien civilization. Hence the name they gave the source LGM 1—LGM for Little Green Men.

A few months before the discovery, Francis Pacini published a theoretical paper showing that a rapidly rotating neutron star with a strong magnetic field could act as an electric generator and emit radio waves. (Once thermonuclear sources of energy are exhausted, stars of less than 1.4 solar mass shrink until they become white dwarfs; more massive stars continue contracting into even more dense stars composed of neutrons.) Most millisecond pulsars, pulsating many times per second, have white dwarf companions, and their amplified spins may be somehow attributable to the accretion of mass from the companion star.

The cosmological hypothesis for quasars—that their red shifts are associated with the expansion of the universe, and they are at great distances from the earth—is generally accepted. Observations by Halton Arp at Palomar, however, suggested possible physical connections between a few quasars and nearby galaxies. A committee at Palomar judged Arp's controversial research to be without value, and terminated his observing time in 1983. Quasars probably are powered by the energy released when matter falls into a gigantic rotating black hole. Why so many quasars have red shifts around 2 remains to be explained.

Norriss S. Hetherington



Computer illustration of a pulsar (a rapidly rotating neutron star) showing its emission process. Energy beams are colored blue and the magnetic fields that contain them, green. If the beams fall on Earth during the pulsar's rotation, it will appear to blink like a light house.